White Paper on Multi-Millisecond (MMS) UWB Operation in IEEE 802.15.4ab

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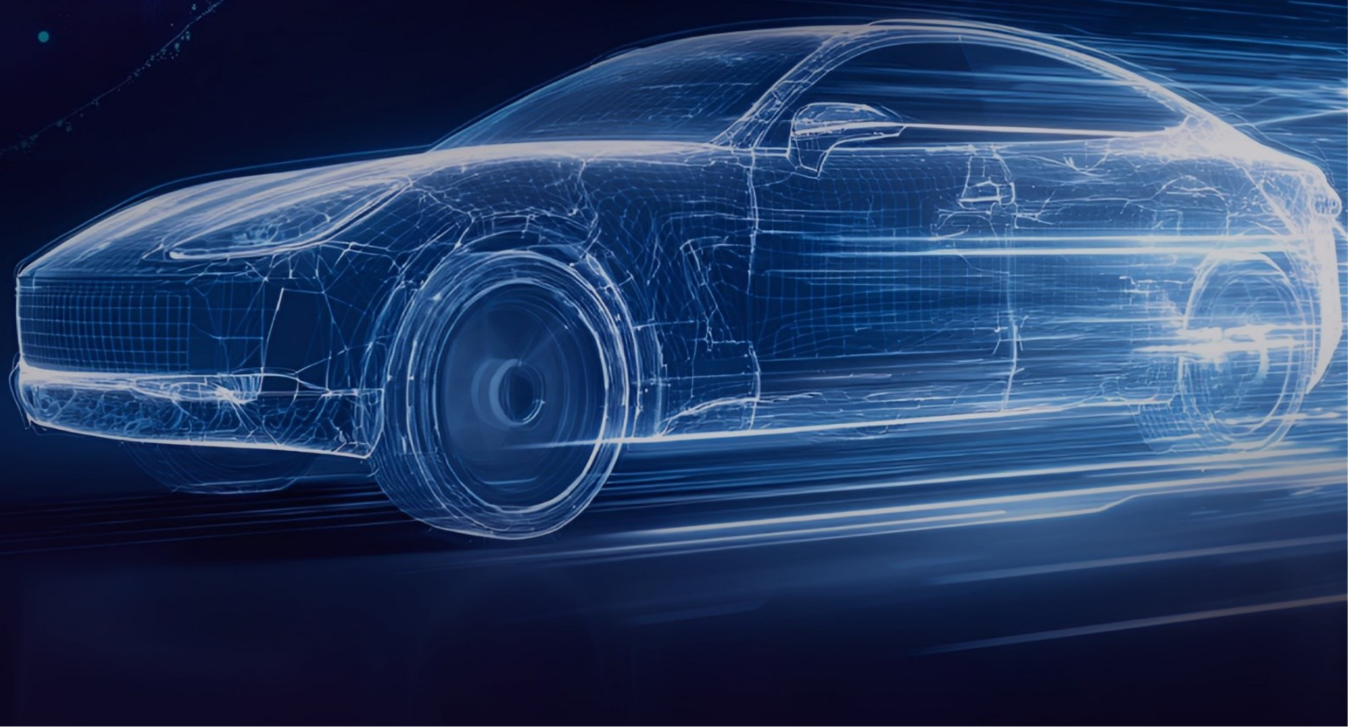
September 2025 (Version 1.0)



Abstract

Ultra-Wideband (UWB) technology has become a leading solution for fine-ranging applications such as indoor positioning, asset tracking, and secure access. However, conventional IEEE 802.15.4z-based UWB ranging[1] still suffers from inherent limitations: strict regulatory power limiting the total link budget of ranging, unstable performance in non-line-of-sight conditions, and multipath interference from environments. As a result, UWB's effective ranging distance is often restricted to a few meters, with degraded stability in real-world deployments.

These challenges are particularly serious in automotive UWB digital key use cases, where reliable passive entry demands accurate detection of user's distance from the car under diverse scenarios. In practice, some typical issues of UWB digital key severely impact user experience, including:

- ranging stability degrading sharply when digital keys are carried in back pockets or bags

- complex environments such as underground parking introducing false first-path detection due to heavy multipath reflection

- UWB anchors inside vehicles facing severe attenuation from metal body structures and glass

To overcome these limitations, IEEE 802.15.4ab (in progress) introduces Multi-Millisecond (MMS) UWB operation[2], in which MMS UWB ranging fragments exchange across multiple milliseconds, enabling accumulation of the channel impulse response (CIR) over multiple milliseconds. This significantly improves the link budget of UWB ranging, extends the reliable ranging distance, and enhances multipath resilience. The standard defines three MMS UWB modes:

- Narrowband-Assisted (NBA) MMS UWB[2]: NBA MMS UWB utilizes a narrowband O-QPSK PHY for MMS control and report phases, and the UWB channel for the MMS ranging phase, which can achieve full MMS gain but requires extra narrowband hardware and new spectrum. This mode also needs to consider the coexistence mechanism with other wireless technologies (e.g., WIFI).

- UWB-Driven MMS UWB[2]: This mode runs the MMS control, ranging, and report phases purely over the UWB channel, simplifying design but constrained by the link budget of control and reporting.

- Out-of-Band (OOB) MMS UWB[2]: This mode offloads MMS control and report phases to external wireless connections, most commonly Bluetooth Low Energy

(BLE), while dedicating the UWB channel exclusively to exchanging MMS ranging fragments.

Among these, BLE-assisted MMS emerges with great potential as a practical approach for digital key enhancement. It matches NBA MMS in full MMS link budget gain without new hardware cost or spectrum requirements, avoids coexistence issues, and leverages the globally harmonized ecosystem of BLE already embedded in smartphones and vehicles.

This white paper presents the principles, modes, and performance analysis of MMS UWB operation in IEEE 802.15.4ab (in progress), with emphasis on its application in automotive digital keys. By extending the effective ranging distance and reliability of UWB through MMS UWB operation[2], the next generation of automotive UWB digital keys can deliver a secure, consistent, and user-friendly experience, while accelerating global deployment.

Keywords:

UWB, MMS, IEEE 802.15.4ab, BLE-assisted MMS, NBA MMS, UWB-driven MMS, Digital Key, Channel Sounding, CIR, RSF, RIF

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1. Introduction

1.1 UWB Technical Background

Ultra-wideband (UWB) is a short-range wireless technology that uses nanosecond-scale pulses (around 2 ns) and spreads over hundreds of MHz in spectrum (>= 500 MHz) with ultra-low power spectral density (<= −41 dBm/MHz by regulation). UWB typically uses BPM/BPSK modulation in association with a high pulse-repetition frequency (PRF). UWB radio emits pulses while keeping the transmission power within the regulatory limit. The large bandwidth of the UWB system leads to a finely resolved channel impulse response (CIR), allowing the receiver to separate early and late multipath signals, which is essential for ranging systems with time-of-flight (ToF) measurement. A UWB system also has very strong resilience to narrowband interference due to its large bandwidth.

In UWB ranging, distance is usually measured from the ToF:

- Devices timestamp the signal transmitting timing and first arriving-path timing and then convert the ToF to distance;
- Double-sided two-way ranging cancels clock offsets between ranging devices;
- Algorithms to reduce multipath interference.

In practice, UWB ranging with accuracy less than 10 cm is achievable in clear LoS conditions.

With the advanced ranging capability and additional sensing and data communication, the UWB technology has emerged as a leading solution for fine-ranging applications such as digital car keys, indoor positioning, and asset tracking.

From a UWB standardization perspective, IEEE 802.15.4 has a rich history of UWB support:

- The IEEE 802.15.4a amendment introduced UWB physical layers and low-rate, high-precision ranging
- The IEEE 802.15.4z amendment enhanced the robustness and security of UWB (e.g., the HRP UWB PHY with scrambled timestamp sequences for secure ranging). Additionally, the amendment offered a new pulse modulation option and a new coding option for better performance and low-rate pulse (LRP) UWB PHY alternatives.

- The IEEE 802.15.4ab amendment (in progress) enhances UWB capabilities in ranging, sensing, and data communication. For UWB ranging, an attractive Multi-Millisecond (MMS) UWB operation is introduced.

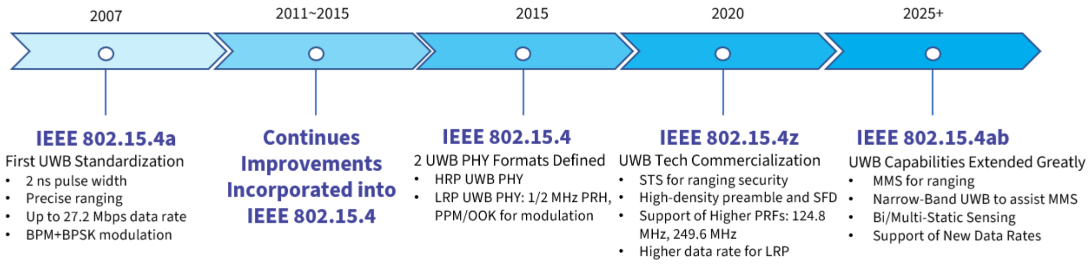

Figure 1: Evolution of IEEE 802.15.4 for UWB

As UWB deployment expands, especially with the commercial launch of IEEE 802.15.4z, use cases of UWB ranging, from localization and passive entry via digital car keys to industrial asset tracking, have emerged with greater ranging distance, better accuracy and security, multi-user scalability, and robust interference mitigation.

Despite these advancements, UWB ranging is still facing a fundamental challenge: transmit power and energy per ranging packet. Regulatory bodies typically impose an effective isotropic radiated power (EIRP) limit averaged over a short time window (-41.3 dBm/MHz per 1 ms) for UWB transmissions, which leads to the limited link budget of UWB ranging signals.

1.2 UWB Technology Market Prospects

UWB technology is one of the most accurate and reliable ranging technologies compared with other wireless technologies. Besides ranging, UWB can also be used in other applications, such as radar sensing with enhanced antenna array. More UWB applications are expected to enter the market in the near future.

Furthermore, integration with smartphones is the key driver fueling the rapid growth of the UWB market. UWB technology is widely applied in the smartphone ecosystem, including chipsets and operating systems, in recent years.

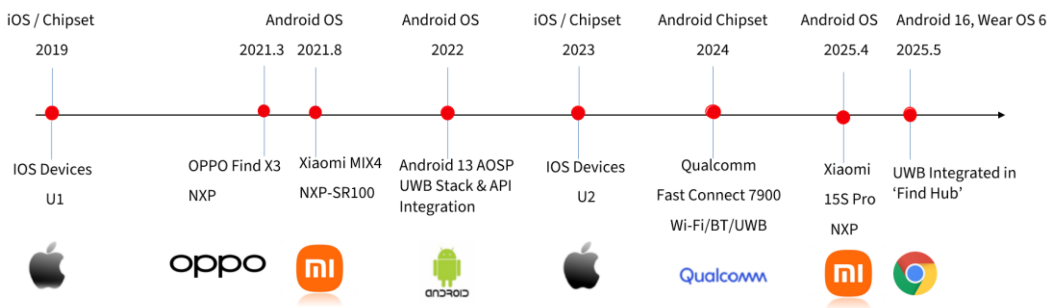

Figure 2: UWB Integration in Smartphone Ecosystem

Data from Techno System Research indicates that the global UWB market will have a significant growth. The shipment volume is forecast to hit 489.7 million units in 2025, which would equate to a 15% year-over-year increase. This expansion is set to continue, with expectations for the market to surpass 1 billion units by 2029. At that stage, smartphones are anticipated to be the largest contributor, making up 50% of the shipments, while the automotive industry will represent a 16% share.

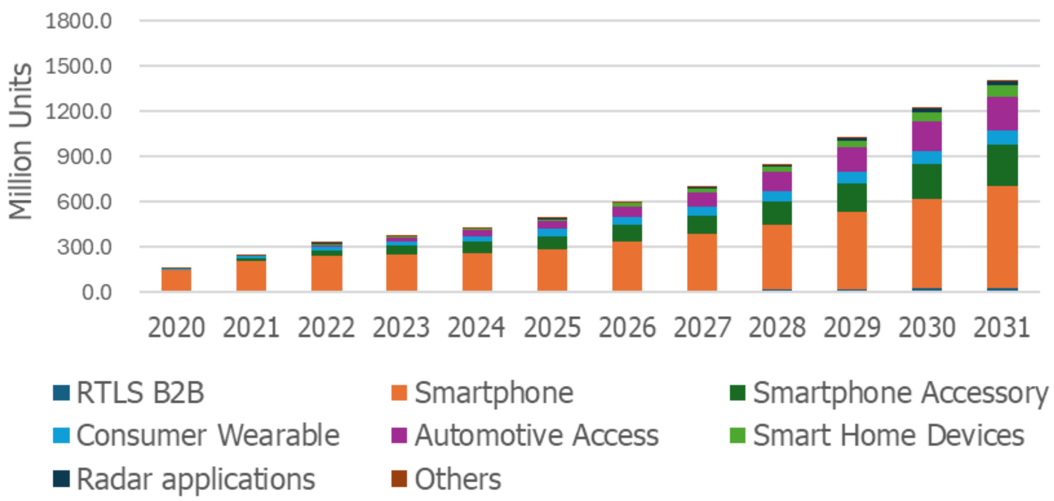

Figure 3: Total UWB Device Shipment Forecast by Main Verticals (2020-2031)

**Source: 2025 UWB & Bluetooth Direction Finding Market Analysis, Gabriella Szucs from Techno Systems Research*

The automotive market represents a very active sector for UWB technology, with secure digital key systems standing out as a major application. Based on current industry data and trends, it is forecasted that UWB technology will see expanded adoption: transitioning from high-end vehicles into mid-range segments, and is expected to be integrated in 47.1% of all vehicles by 2035.

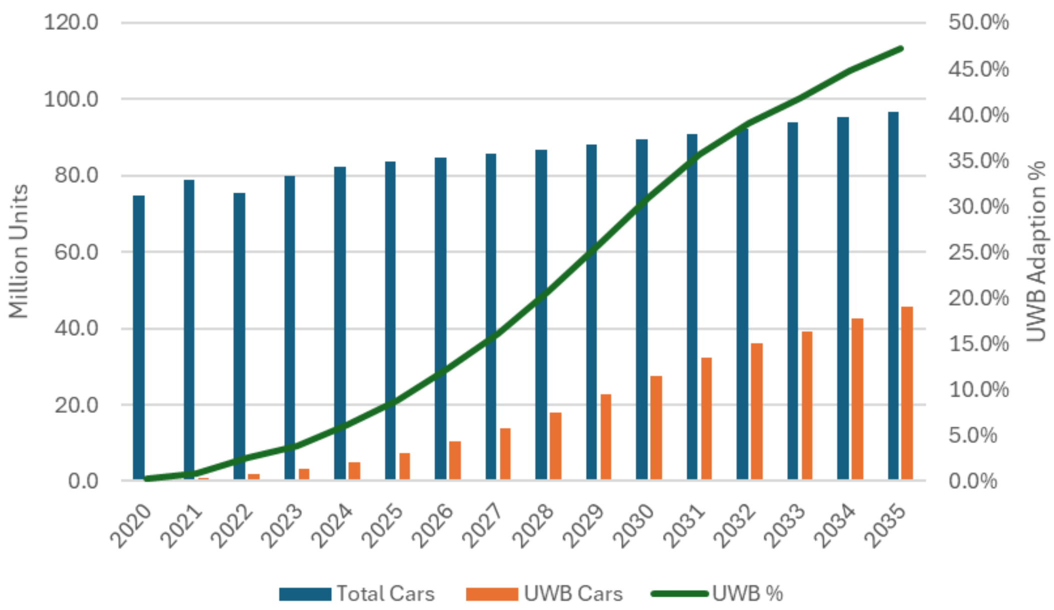

Figure 4: Total UWB Car Adaption Trend Forecast (2020-2035)

**Source: 2025 UWB & Bluetooth Direction Finding Market Analysis, Gabriella Szucs from Techno Systems Research*

Based on the above analysis, UWB is positioned for rapid growth in the automotive market. Improved link budget and reliability (via e.g., MMS ranging) and broader chipset integration in phones and vehicles will further accelerate the worldwide adoption of UWB technology in use cases of automotive digital keys. Beyond automotive, the secure, centimeter-level ranging, and low power advantage of UWB make it compelling for asset tracking, industrial automation, and other consumer devices (e.g., tags, wearables, extended reality). We may expect a bright and expansive future for the UWB technology.

1.3 Challenge of UWB Ranging in Use Case of Digital Car Keys

In the passive entry scenario of digital car keys, UWB is expected to range user's distance early and make unlock decisions without user action. However, two main pain points undermine the user experience of UWB ranging.

1) Limited and unstable ranging distance: short ranging distance (~10 m):

   - Beyond roughly 10 m, automotive UWB anchors often lose connection with the digital key

   - Very limited link budget when the key is in a back pocket due to obstruction by the human body and surrounding obstacles, such as parked cars, walls, and pillars

- Multipath interference: A complicated wireless environment (e.g., underground parking) introduces heavy reflections and non-line-of-sight paths, which leads to the false first-path detection between digital key and vehicle UWB anchor.

- Automotive UWB anchor placement: In-cabin UWB anchor may face more serious attenuation of UWB ranging signals, due to penetration through the metal car body and the glass window.

2) UWB ranging accuracy below expectations: Average ranging error of 20 cm–50 cm.

    - In many field conditions, UWB offers only modest improvement over BLE RSSI ranging, especially when human bodies or objects partially block UWB signals or in rich multipath wireless environment.

Across the industry, expectations for UWB digital car keys are much longer range and higher accuracy:

- Ranging distance over 50 m with precision better than 10 cm.

- With the UWB technology, better intent recognition, more reliable unlock decisions, and a consistent user experience across challenging scenarios can be achieved.

1.4 Evolution Motivation of MMS UWB Operation in IEEE 802.15.4ab

Traditional UWB ranging faces key limitations in ranging distance and reliability for the following reasons:

- Regulatory constraints impose strict limits on the UWB transmit power (e.g. –41.3 dBm/MHz), which limits the communication range and link budget of UWB ranging signals. As a result, many UWB devices can only maintain stable distance measurements in short distances (from a few meters to a few tens of meters) due to insufficient sensitivity of receiving ranging signals at longer range.

- Multipath propagation (especially in complicated reflective environments like indoor car park) can cause ranging instability: multiple reflected paths can interfere with identifying the true first path by UWB ranging devices, which leads to jitter or errors in distance estimation.

In automotive digital key use cases, the challenges mentioned above are particularly serious. A smartphone or key fob must reliably authenticate and measure distance to a vehicle for secure passive entry. Cars often present a harsh RF environment (metal surfaces, car windows, obstructions of other vehicles or human bodies) that can attenuate or reflect UWB signals, which may lead to unreliable UWB ranging measurement and cause false operation of UWB-based unlocking.

In order to address these issues, the IEEE 802.15.4 working group has focused on enhancing UWB range capability and robustness in its latest UWB standard, IEEE 802.15.4ab (in progress).

An important goal of IEEE 802.15.4ab (in progress) is to increase the UWB ranging link budget without violating regulatory limits. The solution introduced is called Multi-Millisecond (MMS) UWB operation[2]. The key idea of MMS UWB operation is to leverage longer UWB ranging exchanges composed of multiple transmitted fragments separated in time (on millisecond scale). By splitting a UWB ranging packet into several short MMS ranging fragments spaced at least one millisecond apart, a device can transmit each MMS ranging fragment at the peak power allowed per millisecond, accumulating more total energy in the channel impulse response (CIR) than that of a single UWB ranging packet. Importantly, because the MMS ranging fragments are interleaved at 1 ms intervals, the average power spectral density remains compliant with regulatory power limits.

MMS UWB accumulates the CIR over multiple milliseconds[2] to significantly boost the energy of received UWB ranging signals and thus improve the receiving sensitivity. This directly translates to greater ranging distances and a more reliable link, as the higher combined energy over the fragments raises the link budget on a large scale. The higher energy accumulated also improves resilience to multipath fading: even if some fragments are corrupted by reflections or interference, others will still contribute to ranging, and the combined signal processing can better distinguish the true first path of the arriving UWB signal, thus a more reliable time-of-flight estimation can be achieved.

By overcoming the ranging distance and multipath limitations, MMS UWB operation can provide great improvements on use cases such as the digital car key.

In the current use case of UWB-based digital car key (built on IEEE 802.15.4z HRP-UWB), the effective ranging distance is typically around 10 meters. With MMS, it is expected that the UWB ranging distance can extend much further without violating regulations.

In summary, MMS UWB operation is motivated by the needs to extend the UWB ranging distance and to improve the stability of ranging measurement for demanding use cases such as digital car key and some other ranging scenarios.

2. MMS UWB Operation in IEEE 802.15.4ab

2.1 Overview of MMS UWB Operation

2.1.1 Definition and Purpose of MMS UWB

Multi-Millisecond (MMS) UWB operation[2] refers to an enhanced ranging packet structure and procedure defined in IEEE 802.15.4ab (in progress) that allows UWB ranging exchanges to span multiple milliseconds for improved performance. It is implemented on the High Rate Pulse (HRP) UWB PHY, supported by advanced UWB ranging devices (HRP-ARDEV[2]). The MMS UWB technique accumulates the CIR estimate from a sequence of fragments sent in separate milliseconds to utilize the regulatory transmit power budget per millisecond.

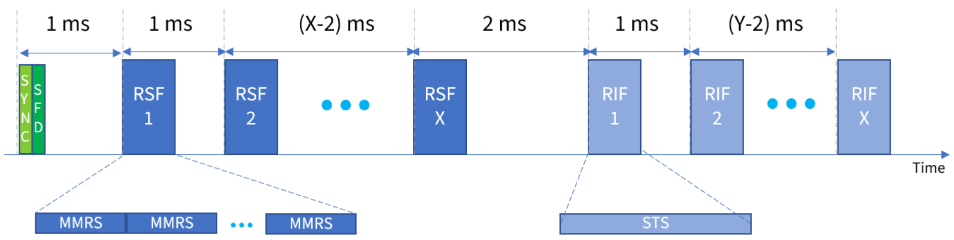

Figure 5: MMS UWB Ranging Transmission

In a traditional two-way ranging (TWR) session (as in IEEE 802.15.4z), an initiator device and a responder device perform exchanges consisting of UWB ranging packets (802.15.4z based SP3) within a span of a few milliseconds.

In MMS UWB operation, the initiator and responder can exchange multiple MMS ranging fragments at a 1 ms time granularity. By combining multiple identical MMS ranging fragments received, the receiving sensitivity is significantly enhanced. Additionally, in the MMS UWB ranging scheme, packets of control data and ranging result reporting data can be transmitted via BLE or Narrowband UWB connections. Therefore, the receiving sensitivity for both MMS ranging fragments and data packets involved in an entire UWB ranging procedure is significantly enhanced.

The IEEE 802.15.4ab (in progress) standard defines multiple ways to initiate and coordinate an MMS UWB ranging exchange, depending on which wireless technology is used for transmitting packets of control data and ranging result reporting data during the MMS UWB procedure. However, the core MMS UWB operation concept — transmitting MMS ranging fragments over multiple milliseconds—remains the same. There are three modes for MMS UWB ranging:

1) Narrowband-Assisted MMS UWB (NBA MMS UWB): A separate narrowband PHY (O-QPSK) is used for MMS UWB session setup, control, and report phases. The narrow band O-QPSK PHY shares a common clock source with the UWB PHY, to determine the clock offset to assist the accumulation of MMS ranging fragments.

2) UWB-Driven MMS UWB: HRP UWB PHY is used for all phases (control, ranging and report phase). MMS UWB session setup is still performed via narrowband (NB) or out-of-band (OOB) connection.

3) OOB MMS UWB: An out-of-band technology (commonly Bluetooth Low Energy [4]) is used for the MMS UWB session setup and the control and report phases, with HRP UWB PHY used only for the MMS ranging phase.

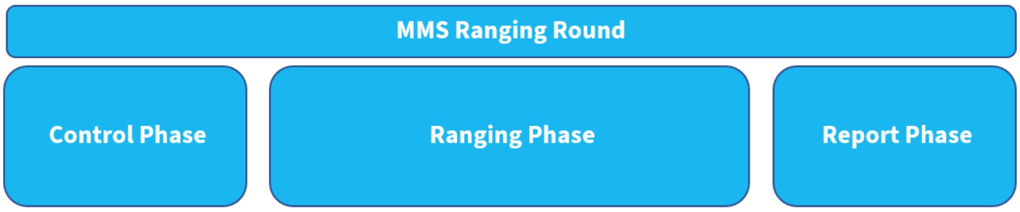

Figure 6: Phases in MMS UWB Ranging

Each mode has its own advantages and ideal use cases. All three MMS UWB modes aim to facilitate the exchange of MMS ranging fragments, but differ in how they initiate the ranging session and manage synchronization and data packet transfer in the control and report phases.

2.1.2 Key Technical Principles of MMS UWB

MMS UWB operates on two core principles:

1) Fragmentation: UWB ranging signals are split into multiple short MMS-ranging fragments, Ranging Sequence Fragments (RSFs) and Ranging Integrity Fragments (RIFs), transmitted across consecutive milliseconds. This allows devices to comply with per-millisecond power regulations while boosting the transmission energy on each short MMS-ranging fragment.

2) CIR Accumulation: The receiver accumulates CIR estimates from all MMS-ranging fragments to improve the signal-to-noise ratio (SNR), enhancing

sensitivity and enabling reliable ranging even in challenging environments (e.g., multipath-rich or low-signal conditions).

Depending on the MMS UWB mode applied, the HRP UWB PHY MMS packet may include a combination of an initial SYNC+SFD fragment, RSFs, and RIFs[2].

2.2 MAC Enhancement of MMS UWB Operation

2.2.1 MMS UWB Device Roles and Ranging Structure

2.2.1.1 MMS UWB Device Roles

In an MMS UWB session, there are two roles:

- Initiator (Controller): The initiator is the controller of the MMS UWB session. It decides the MMS session configuration (MAC/PHY parameters of MMS) and when to begin the MMS exchange (control/ranging/report phase).

- Responder (Controlee): The device (or devices) responds to the initiator's requests. The responder (or controlee) follows the initiator's configuration in the MMS session.

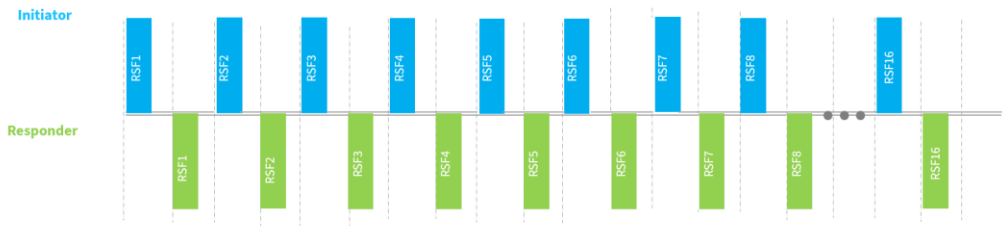

Figure 7: MMS UWB Ranging Transmission Between Two Devices

For one-to-one MMS UWB ranging, there is a single initiator and a single responder. For one-to-many MMS UWB ranging, one initiator manages multiple responders involved.

2.2.1.2 MMS UWB Ranging Structure

MMS UWB operation reuses the ranging block and the round structure defined in IEEE 802.15.4, with adaptations for fragment-based transmission:

1) MMS Ranging Block: A time period containing multiple ranging rounds

2) MMS Ranging Round: A sub-period comprising an MMS control phase, an MMS ranging phase, and an optional MMS report phase

3) MMS Ranging Slot: A time unit (typically 1 ms) allocated for MMS fragment transmission

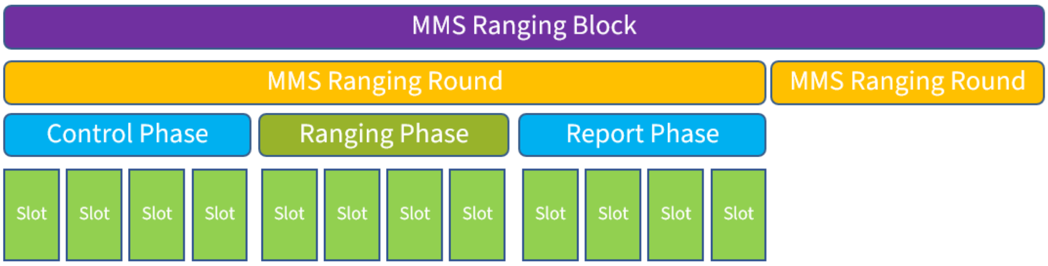

Figure 8: MMS UWB Ranging Block Structure

For one MMS UWB session, the slot, round, and block durations must be integer multiples of 300 ranging slot time units (RSTUs) to ensure timing alignment[2].

Before initiating MMS UWB ranging, devices must complete an initialization and setup phase to negotiate parameters such as UWB channel usage, modulation schemes, and MMS fragment configuration by using either NB connection or OOB connection (typically BLE connection).

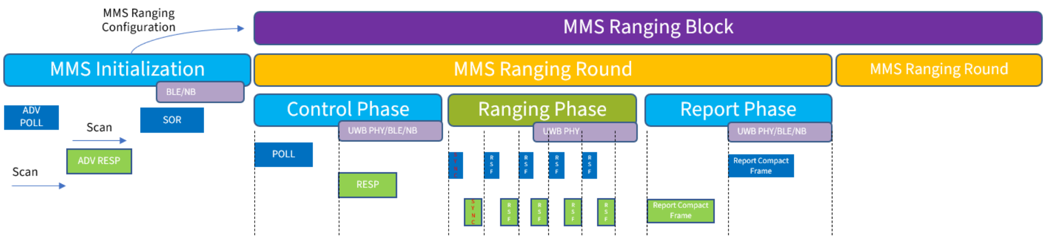

Figure 9: MMS UWB Ranging System Block

Each MMS UWB ranging round consists of three phases:

1) Control Phase[2]: Devices exchange compact frames (e.g., Poll and Response) to negotiate short-term MMS parameters for the current ranging round or long-term MMS parameter for the next and subsequent ranging rounds. The control phase can use the NB channel (in NBA MMS UWB), the UWB channel (in UWB-driven MMS UWB), or OOB connection (in OOB MMS UWB).

2) Ranging Phase[2]: Devices transmit or receive MMS ranging fragments (SYNC+SFD, RSFs, RIFs) for CIR estimation and accumulation. The initiator and responder may interleave transmit MMS fragments in each millisecond with a 600 RSTU offset (0.5 ms). The ranging phase uses the UWB channel to exchange the MMS fragments between devices.

3) Report Phase[2]: Optional phase for exchanging ranging results (e.g., round-trip time or reply time) using compact frames. The report phase can use the NB channel (in NBA MMS UWB), the UWB channel (in UWB-driven MMS UWB), or OOB connection (in OOB MMS UWB).

2.2.2 Initialization and Setup of MMS UWB Session

Before entering the MMS UWB session, the devices need to share an MMS UWB session configuration—a common understanding of parameters such as:

- Management MAC Configuration[2]: Slot, round, and block configurations for control, ranging, and report phases
- Management PHY Configuration[2]: PHY configuration of channels (NB or UWB channels), modulation, and data rate to be used for control and report phases
- Ranging PHY Configuration[2]: PHY configuration of UWB channels to be used for the ranging phase
- Numbers of MMS Fragments[2]: Numbers of MMS fragments (RSF/RIF) will be used in the ranging phase.

This configuration can be established either explicitly through an MMS UWB initialization and setup phase or implicitly via pre-configuration. IEEE 802.15.4ab (in progress) provides an Initialization and setup phase prior to the MMS UWB session (control, ranging, and report phases).

In an initialization and setup phase, devices may exchange the compact frames used for MMS initialization:

- An Advertising Poll Compact Frame[2]: Advertising by an initiator in order to look for MMS ranging responder(s) and announcing a UWB MMS ranging session and the configurations of the related initialization slot and the supported NB.
- A Response Poll Compact Frame[2]: Sent by a prospective responder to indicate response to join the MMS UWB session. The responder can also transmit its preferred MMS MAC or PHY configuration for the upcoming MMS UWB session based on its capability.
- An Advertising Confirmation Compact Frame (Optional)[2]: Advertising by an initiator to indicate the time offset to the start-of-ranging (SOR) compact frame[2] for respective responder. In order to mitigate the multi-session UWB channel interference, the initiator will use this time offset to capture the surrounding

MMS UWB session information, which will be used in the decision of the configuration of its upcoming MMS UWB session.

- A Start-of-Ranging (SOR) Compact Frame[2]: Sent by an initiator, which is used by the initiator to signal the time offset to the upcoming MMS UWB session (control, ranging, and report phases) with the agreed MMS configuration.

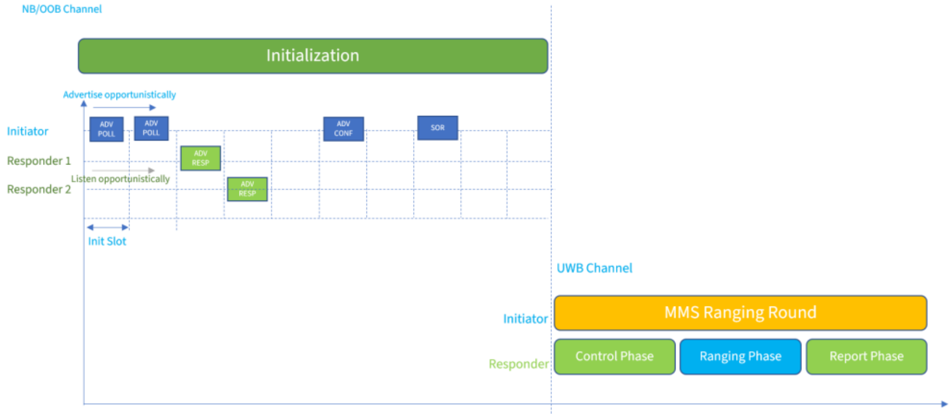

Figure 10: MMS UWB Ranging Initialization

During the process of the MMS UWB initialization and setup phase, the devices can negotiate and configure the MMS UWB session settings other than the default configuration. This process ensures that by the time the control phase of the first ranging round begins, both the initiator and responder know the essential details (UWB or NB channel, timing, etc.) of how they will conduct the MMS exchange.

2.2.3 MMS UWB Control Phase

The MMS UWB control phase[2] is a short phase where the initiator communicates with the responder(s) to kick off the ranging exchange for that MMS UWB ranging round.

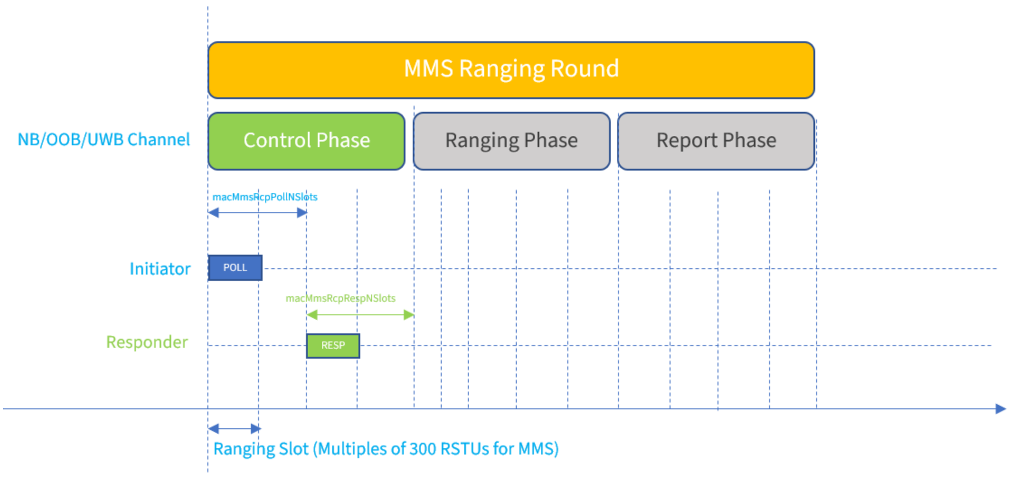

Figure 11: Control Phase in MMS UWB Ranging

In one-to-one MMS UWB ranging, the control phase typically consists of the initiator sending a poll compact frame[2] and the responder replying with a response compact frame[2].

In one-to-many MMS UWB ranging, the initiator might send a broadcast poll compact frame and then multiple responders contend or take turns to send a response compact frame, or the initiator could allocate time slots for each responder.

During the control phase, the devices may renegotiate the short-term or long-term parameters including the management MAC and PHY parameters, the ranging PHY parameters, and numbers of MMS fragments for the MMS UWB session:

- Control phase to update the short-term parameters: The initiator may override the short-term operating parameters for the current ranging round.
- Control phase to update the long-term parameters: The initiator may also update the long-term operating parameters for the next and subsequent ranging rounds.

The control phase process is carried out on the narrowband PHY in NBA MMS UWB, or over UWB PHY in UWB-driven MMS UWB, or OOB connection (typically BLE connection) in OOB MMS UWB.

In NBA MMS UWB, the control phase can also handle channel access using mechanisms like listen-before-talk (LBT). For example, if the NB channels running on the UNII-3 and UNII-5 are shared with other wireless technologies, the initiator may perform clear channel assessment (CCA) and possibly random backoff before sending the compact frame to avoid collisions. In some regions, devices operating on certain bands must perform LBT to avoid interfering with other wireless systems (such as Wi-Fi, etc.).

2.2.4 MMS UWB Ranging Phase

The MMS UWB ranging phase[2] is the core of the MMS UWB operation where the actual multi-millisecond ranging fragments exchange occurs. At the start of the ranging phase, the initiator and the responder switch to the designated UWB channel and prepare to transmit and receive the MMS ranging fragments. The initiator will send its MMS ranging fragments and the responder will send its MMS ranging fragments. There are two possible patterns here:

1. Interleaved MMS ranging fragments exchange[2]: Typically, MMS UWB operation is performed with interleaving, meaning the initiator’s and responder’s MMS

ranging fragments alternate in each 1 ms slot with the time offset equal to 600 RSTUs (0.5 ms). For example, the initiator sends MMS Ranging Fragment 1 at time T_0, then the responder (who received MMS Ranging Fragment 1) sends its MMS Ranging Fragment 1 at time $T_0 + 0.5$ ms. In this way, both devices are transmitting and receiving fragments in an interleaved manner.

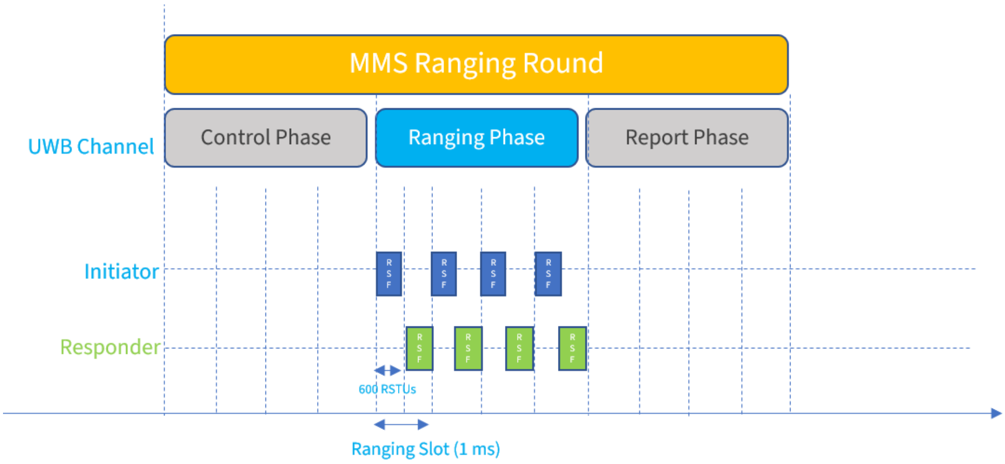

Figure 12: MMS UWB Interleaved Ranging Phase

Interleaving has an advantage, a shortened duration of a round, by effectively merging the transmissions of two devices, instead of sending them sequentially.

2. Non-Interleaved MMS ranging fragment exchange (optional)[2]: In some cases, devices may use a non-interleaved approach, where one device transmits all its MMS ranging fragments in a burst and then the other device transmits all its MMS ranging fragments in another burst. This might be used if a device cannot rapidly switch between Tx and Rx or to simplify certain scenarios.

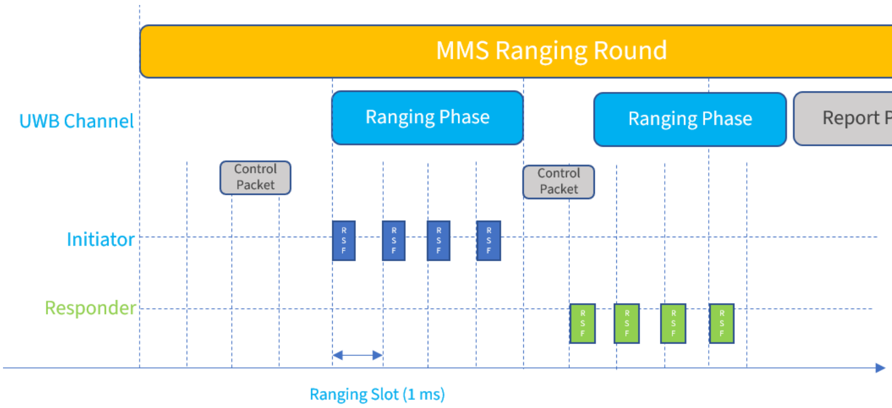

Figure 13: MMS UWB Non-Interleaved Ranging Phase

Three kinds of MMS fragments are defined in IEEE 802.15.4ab (in progress) :

- SYNC+SFD Fragment[2]: Enabling initial synchronization between the transmitter and the receiver. SYNC+SFD is defined as the first MMS fragment for UWB-driven MMS and OOB MMS UWB (optional).
- RSFs[2]: Carrying the main MMS-ranging sequence, with lengths configurable via the RSF Fragment Length field.
- RIFs[2]: Providing integrity checks and additional CIR data, with lengths specified by the RIF Fragment Length field.

During the MMS UWB ranging phase, tight timing control is required:

- Each MMS UWB fragment transmission starts exactly on a 1 ms boundary relative to the session start.
- For interleaved MMS fragment exchange, each MMS fragment from the respective initiator and responder with the precise time offset is equal to 600 RSTUs (0.5 ms) in each 1 ms ranging slot.
- If both RSFs and RIFs are configured within the MMS UWB ranging packet, the time offset between the first RIF and the last RSF shall be 2 ms. This applies to both initiator and responder devices.

Within the ranging phase, the PHY layer of the device takes the high-level parameters (such as the numbers of MMS fragments and the type of MMS fragments) and translates them into actual UWB MMS signals. We will detail the PHY format in a later section.

From a system's point of view, the MAC indicates the PHY to send an MMS packet (e.g., X RSFs and Y RIFs) and the PHY then handles the generation of pulses and insertion of gaps as required. The MAC also schedules the reception window for expected incoming MMS ranging fragments from the other UWB device. If a fragment is missed (e.g., due to interference), the MMS ranging round might still continue but the measurement quality of the round may degrade.

2.2.5 MMS UWB Report Phase

After the exchange of MMS ranging fragments, an optional MMS report phase can occur. The report phase conveys ranging results (e.g., round-trip time, reply time) between devices, using compact frames such as one-to-one or one-to-many initiator /responder report compact frame[2]. In a two-way ranging scenario, typically each side needs some information from the other to finalize a ranging computation:

- Round-Trip Time (RTT): Measured by the initiator as the time between transmitting its MMS fragment and receiving the responder's MMS fragment.
- Reply Time: Measured by the responder as the time between receiving the initiator's MMS fragment and transmitting its MMS fragment.

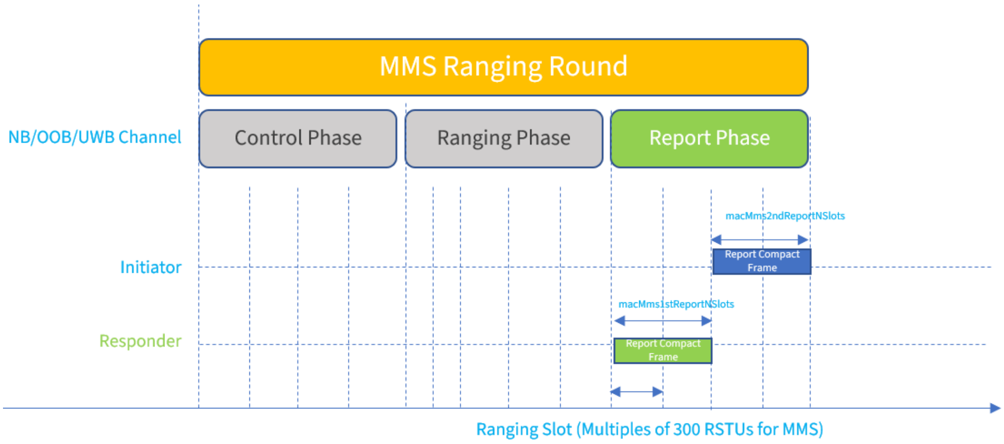

Figure 14: Report Phase in MMS UWB Ranging

During the report phase, the initiator and responder may exchange an Initiator Report Compact Frame and a Responder Report Compact Frame[2] over the narrowband channel in the NBA MMS UWB, a UWB-data frame over the UWB channel in UWB-driven MMS UWB, or an OOB-data frame over OOB connection (typically BLE connection) in OOB MMS UWB. The report phase is optional because in some cases, this phase may not necessarily occur every time in every MMS ranging round, the devices may combine and exchange the ranging results only in some dedicated MMS ranging rounds. However, for maximum accuracy and to enable double-sided ranging, the report phase is generally required.

After the report phase finishes, the subsequent ranging rounds continue in an MMS UWB session (for example, ten rounds might be performed to continuously update the distance in a tracking scenario).

For NBA MMS, the initiator might switch to a different narrowband channel (with the responder following) according to an agreed NB-channel-switching scheme to reduce interference or comply with spectrum use policies.

2.2.6 One-to-Many MMS UWB Operation

In one-to-many MMS ranging[2], an initiator can range with multiple responders in one MMS UWB session. Generally, there are four one-to-many MMS UWB modes defined in IEEE 802.15.4ab (in progress):

- Basic One-to-Many MMS UWB Mode[2]: The initiator arranges multiple devices in sequence in their respective sub-rounds within a round. Each sub-round consists of the control, ranging, and report phases. However, doing this sequentially increases the round time linearly with number of devices, which is not time-efficient.

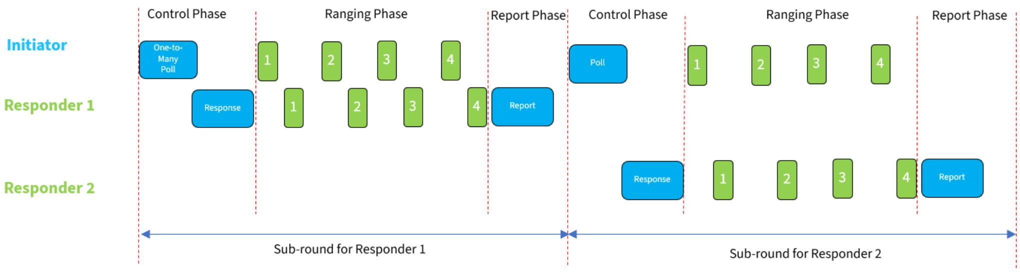

Figure 15: Basic One-to-Many MMS UWB Mode

- Contention-Based One-to-Many MMS UWB Mode[2]: The initiator sends one poll compact frame and multiple responders may reply. Then the initiator may make the decision and sort all or some of them over multiple sub-rounds.

- Time-Efficient One-to-Many MMS UWB Mode[2]: This mode targets time-sensitive applications like AR and VR and introduces methods to reduce MMS ranging latency. Instead of doing MMS ranging fragment exchange with just one responder in a ranging slot, the initiator could perform the exchange with two responders in one ranging slot.

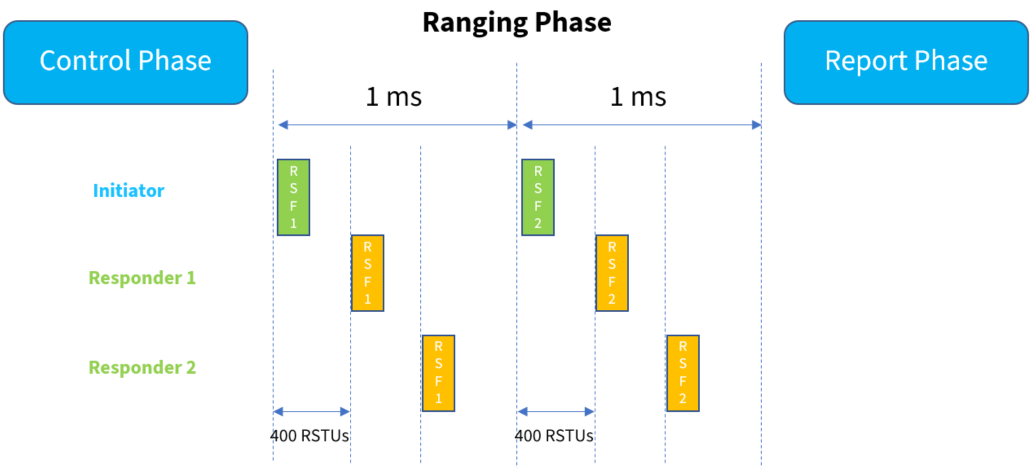

Figure 16: Time-Efficient One-to-Many MMS UWB Mode

- In each sub-round, the initiator may start transmitting the first UWB RSF fragment at the start of the ranging phase, and continue to send the second UWB RSF at an interval of 1200 RSTUs.
- The responder with the Time Shift Indication field set to *zero* may start transmitting the first UWB RSF fragment 400 RSTUs into the ranging phase, and continue to send the second UWB RSF fragment at an interval of 1200 RSTUs.
- The responder with the Time Shift Indication field set to *one* may start transmitting the first UWB RSF fragment 800 RSTUs into the ranging phase, and continue to send the second UWB RSF fragment at an interval of 1200 RSTUs.

- Multiple RSF Transmissions per Slot MMS UWB Mode[2]: In this mode, multiple responders transmit in the same timeslot and may be separated either by code or slight timing offsets. For example, three responders could both transmit their RSFs in the same 1 ms slot, without a strict time offset among the RSFs in the ranging phase, which means each RSF may overlap with the others in the time domain. The initiator may hear three responses in the same slot and can separate them.

2.2.7 Security for MMS UWB Operation

2.2.7.1 Security for MMS UWB Compact Frames

Security can be enabled for the following compact frames[2]:

- One-to-one poll compact frame
- One-to-one response compact frame
- One-to-many poll compact frame
- One-to-many response compact frame
- One-to-one initiator secure report compact frame
- One-to-one responder secure report compact frame
- One-to-many initiator secure report compact frame
- One-to-many responder secure report compact frame

The sending device will encrypt or authenticate the compact payload using the IEEE 802.15.4 AES-CCM algorithm framework, and then the receiving device will decrypt or verify the payload. In practice, this means MAC can be instructed to apply a certain key and security level when sending and receiving a compact frame.

For example, an initiator might use a pre-shared key with the responder to secure compact frames, so that only they can interpret them. This protects against spoofing attacks on the MMS control and report phases.

2.2.7.2 Private Address for MMS UWB Compact Frames

To prevent tracking of HRP-ARDEVs[2], resolvable private addresses (RPAs) are utilized by initiator and responder devices. For RPA generation, each device must employ a 128-bit identity resolving key (IRK). During session initialization, the initiator transmits a 3-octet random bit sequence, termed the RPA PRAND, in every advertising poll compact frame and during ranging the control phase.

The hash field value of 3-octet RPA is computed using an IRK and the initiator’s RPA PRAND. This hash value corresponds to Bits 0–23 of the output from the AES-128 block cipher, where the input parameters are the IRK and the initiator’s RPA PRAND.

When decoding the RPA of an incoming packet, the receiving device computes the RPA hash field using one or more IRKs presumed to have been used by the sender, along with the PRAND value received via the air interface. A match between the computed and received hash values confirms successful RPA resolution; otherwise, the RPA is flagged as invalid and the packet is discarded.

Generating and exchanging IRKs between initiators and responders is a prerequisite for private address resolution. Devices may support multiple IRKs to enforce privacy in multi-device scenarios.

2.3 PHY Enhancement of MMS UWB Operation

2.3.1 General PHY Enhancement

An IEEE 802.15.4ab (in progress) HRP-UWB PHY that supports the MMS UWB mode shall be capable of both transmitting and receiving the MMS ranging fragment (SYNC+SFD, RSF, RIF) in each separated 1 ms ranging slot. The device that supports MMS UWB mode is termed an HRP-ARDEV[2].

In MMS UWB modulation, a packet intended for ranging measurements is composed of several MMS ranging fragments, each sent in a separate millisecond. This approach leverages the per-millisecond regulatory transmit power budget, allowing each fragment to be transmitted at nearly the regulatory maximum. This enables the receiver to process multiple fragments for enhanced sensitivity.

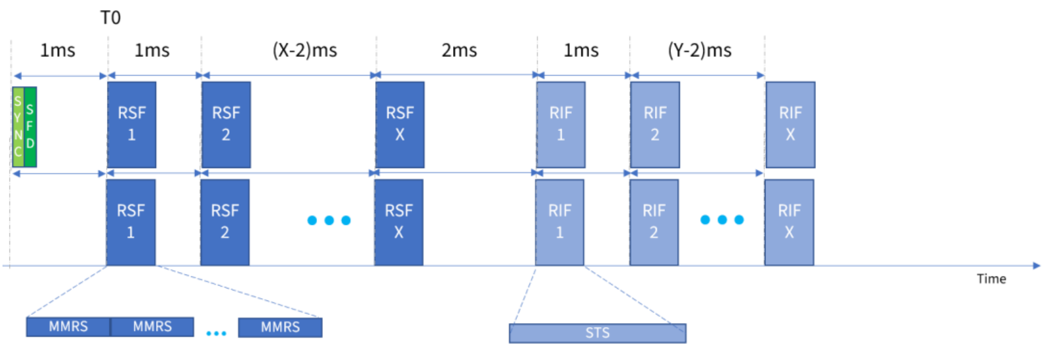

Figure 17: MMS UWB Ranging Fragments

The MMS ranging fragments include three types:

- A fragment containing SYNC and SFD, which is the first fragment exchanged in UWB-driven MMS or OOB MMS UWB (optional)
- RSF, which is used for CIR estimation and accumulation
- RIF, which is used for MMS ranging integration protection

MMS ranging fragment configurations vary according to different MMS UWB modes:

- NBA MMS UWB: RSFs and/or RIFs
- UWB-driven MMS UWB: SYNC and SFD, RSFs and/or RIFs
- OOB MMS UWB: SYNC and SFD (optional), RSFs and/or RIFs

During MMS ranging fragments transmission, all RSFs and RIFs are aligned to millisecond offsets relative to T_0, which marks the transmission start time of the first RSF or RIF.

When transmission of MMS ranging fragments contains both RSFs and RIFs, the timing gap between the first RIF and the last RSF shall be 2 ms.

If present, the SYNC and SFD fragment will start at the same millisecond offset as the first fragment, specifically, 1 ms before T_0.

The HRP-ARDEV shall support the following combinations for either NBA MMS UWB operations or UWB-driven MMS UWB operations:

- RSF-only MMS packets: Y=0, X∈ {1,2,4,8,16}[2]

- RIF-only MMS packets: X=0, Y∈ {1,2,4,8}[2]

- Mixed RSF/RIF MMS packets: X∈ {1,2,4,8}, Y∈ {1,2,4,8}[2]

Where X is defined as the number of RSFs, Y is defined as the number of RIFs within an MMS UWB session.

When RSFs are present, RMARKER is defined as the instant when the peak of the first pulse in the first RSF arrives at the local antenna. When RIFs are present, two RMARKERs are assigned to each RIF fragment, representing the peak times of the first and the last pulses in that RIF fragment.

2.3.2 MMS UWB Ranging Fragments

Type 1: SYNC+SFD Fragment

Function: Synchronization and packet start identification.

Implementation: The fragment sequence adopts the SYNC+SFD sequences defined in IEEE 802.15.4z. The SYNC sequence supports three lengths: 31, 91, and 127[1].

Type 2: RSF (Ranging Sequence Fragment)

Function: Core MMS ranging fragment in the UWB MMS ranging phase for Time-of-Flight (ToF) estimation.

Structure: Composed of repeated MMRS (Multi-Millisecond Ranging Sequence) symbols[2], with the following rules:

MMRS Symbol Generation: Using a 128-bit binary code (+1, -1) newly defined in IEEE 802.15.4ab (in progress), splitting the 128-bit code into two segments (A and B, each 64 bits), and inserting a zero gap (G) of 0-bit–64-bit length to form an AGBG structure.

Spreading extension: Expanding via a spreading factor of L=4 to generate the final MMRS symbol.

Alternatively, the RSF supports MMRS generation using the 91-bit or 127-bit SYNC sequences of IEEE 802.15.4z (also with a spreading factor L=4)[1].

MMRS Usage Rule: Uniqueness. All RSF fragments in the same MMS ranging phase must use identical MMRS symbols.

RSF Length Definition: Determined by the Multi-millisecond Repetition (MSR) count, where MSR count ∈ {32, 40, 48, 64, 128, 256}[2].

Type 3: RIF (Ranging Integrity Fragment)

Function: Ensures security and integrity of UWB MMS ranging.

Implementation: Utilizes the STS (Scrambled Timestamp Sequence)[1] defined in IEEE 802.15.4z, generated via a DRBG (Deterministic Random Bit Generator). Each RIF sequence length is 32, 64, 128, or 256 chips.

The transmitter generates non-repeating RIF sequences using configured DRBG parameters, and then the receiver regenerates identical non-repeating RIF sequences using the same parameters and verifies integrity by comparing them with the received sequences.

3. MMS UWB Modes and Comparison

3.1 Narrowband-Assisted (NBA) MMS UWB

3.1.1 Overview of NBA MMS UWB

In NBA MMS UWB ranging, the NB O-QPSK PHY[2] is employed during the initialization, setup, control, and report phases of the MMS UWB process. This approach uses a narrowband channel to coordinate UWB MMS ranging and execute the ranging result transmission.

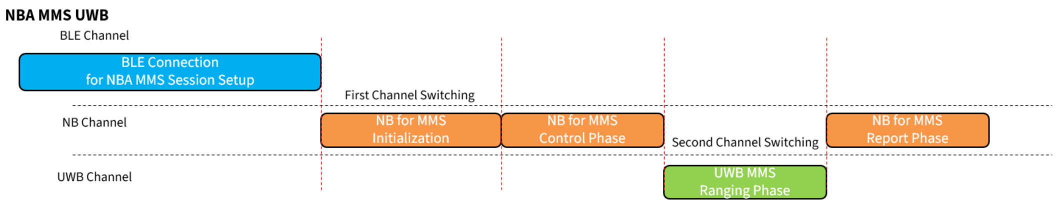

Figure 18: NBA MMS UWB

3.1.2 NB O-QPSK PHY

The NB O-QPSK PHY operates within a defined subset of channels selected from the 250 channels in UNII3 and UNII5 with the 2.5 MHz channel bandwidth.

Band Designation (MHz)	Frequency Band (MHz)
5800	5725–5850
6200	5925–6425

Table 1: Spectrum of NB O-QPSK PHY[2]

The NB O-QPSK PHY supports various modulation configurations and data rates, including optional dynamic data rate signaling via SFD patterns. Three data rates are supported by the NB O-QPSK PHY:

- 250 kbps (mandatory)
- 500 kbps (optional)
- 1000 kbps (optional)

Dynamic SFD patterns allow the NB O-QPSK PHY to indicate the modulation and data rate configuration in-band. Each SFD pattern corresponds to a specific data rate and modulation setup.

3.1.3 Listen-Before-Talk (LBT) for NB Channel

UNII3 and UNII5 bands usually work with Wi-Fi, so when regulatory or coexistence requirements apply, LBT must be performed before each NB O-QPSK PHY transmission. Clear Channel Assessment (CCA) may be executed before transmission. If the channel is clear, transmission shall start within 16 µs after completing the CCA[2]. If the channel is busy, the transmission for that ranging round is skipped.

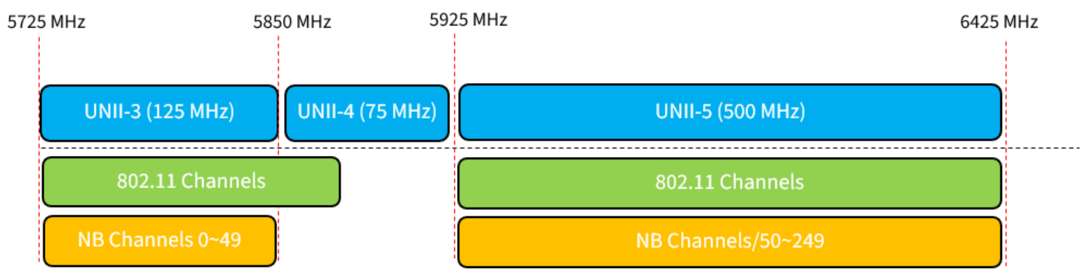

Figure 19: Spectrum Occupation in UNII-3 and UNII-5

In MMS UWB control and report phases, LBT is applied for both the initiator and the responder during their respective slots.

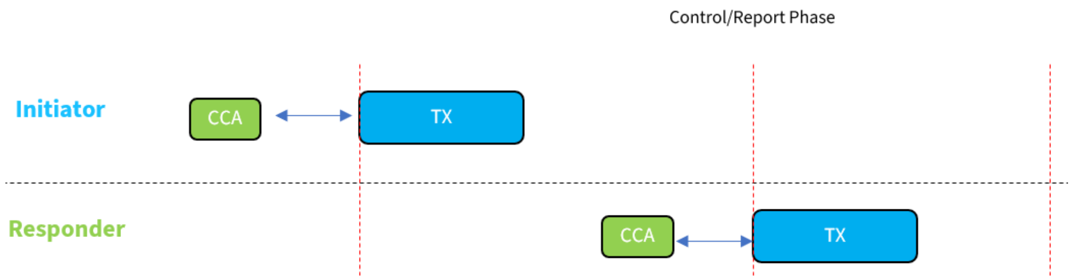

Figure 20: LBT Mechanism Before NB Transmission

LBT generally applies to Channels 50–249 under regulatory rules[2], but in the absence of such constraints, it may be applied to all channels to improve coexistence.

3.1.4 Channel Switching for NB Channel

Because NB O-QPSK transmission uses only a fraction of the available spectrum, NBA MMS supports frequency diversity through channel switching to mitigate fading and improve robustness.

A list-based channel access method is defined, enabling both the initiator and the responder to select from a coordinated set of channels.

For each successive ranging block, the coordinated NB channel can be dynamically updated via the NB Channel field in the poll compact frame (short-term) or via the NB Channel Map field for longer-term configurations. The NB channel dynamically switches among the coordinated channels for each successive ranging block.

NB channel switching is optional. Restricting the NB Channel Map field to a single channel effectively disables it[2].

3.1.5 Key Advantages and Challenges for NBA MMS UWB

NBA MMS enables robust control signaling for its sessions via O-QPSK narrowband links in the 5.8 GHz and 6.2 GHz bands. It can achieve the full MMS link budget and long-range capability.

Key advantages of NBA MMS UWB include:

- Tight coupling with UWB and inherent time-synchronization advantage

  NBA MMS uses an IEEE defined O-QPSK narrowband PHY that shares a common clock source with the UWB PHY, enabling direct clock-offset determination to assist CIR accumulation across MMS ranging fragments. This tight coupling yields native robustness in time and frequency alignment between the NB channel and the UWB channel.

  Note: The IEEE 802.15.4ab (in progress) standard only specifies the sharing clock source requirement for the NB and UWB channels, but does not detail a concrete UWB and NB time synchronization method, which remains implementation-dependent.

- No dependency on out-of-band technologies

The NB O-QPSK PHY used by NBA MMS is defined within IEEE 802.15.4 and carries the initialization, control, and report phases natively, avoiding reliance on out-of-band stacks (e.g., BLE from the Bluetooth SIG). This keeps the entire MMS UWB operation inside the IEEE ecosystem, allowing tighter integration and evolution with the IEEE standard.

However, NBA MMS deployment still faces three main challenges:

- Listen-Before-Talk (LBT) issue:

  In the 5.8 GHz and 6.2 GHz narrowband spectrum, NBA MMS typically should perform Clear Channel Assessment (CCA) before each NB transmission to comply with coexistence requirements. In congested environments, frequent CCA busy results can block transmissions, causing failures or degraded performance of UWB MMS ranging sessions. And the per-slot LBT process also adds latency and increases control complexity in both the initiator and responder roles.

- Spectrum policy uncertainty

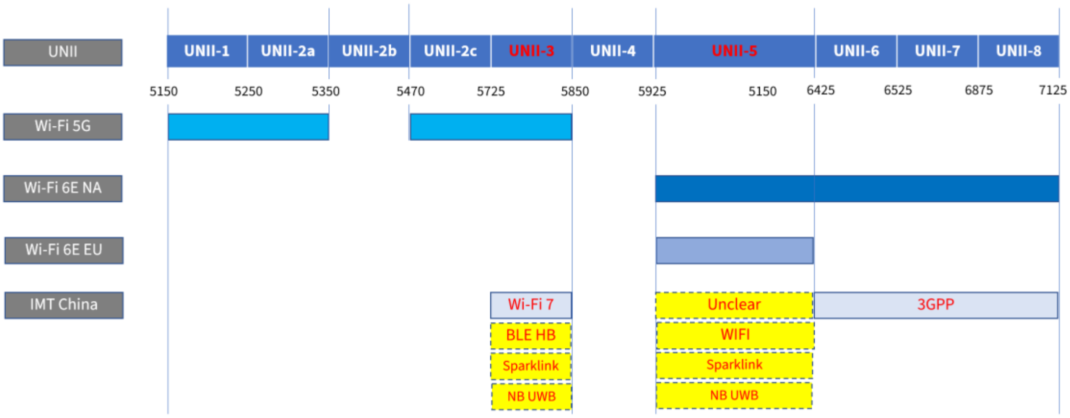

Figure 21: Overall Spectrum Allocation

  NBA MMS relies on NB O-QPSK channels (50 channels on 5800 MHz, 200 channels on 6200 MHz) whose regulatory status is not yet harmonized worldwide. In some key automotive markets (e.g., China), the allocation and usage policy for these NB channels is unclear, potentially delaying market adoption. Coexistence with Wi-Fi 6E/7, ETC, V2X, SparkLink and other wireless systems in overlapping bands increases the risk of interference and further complicates deployment planning.

- Increased hardware, software, and interoperability cost

  Supporting NBA MMS requires additional narrowband hardware alongside the existing UWB chain, including dedicated NB transceiver paths, filters, and antennas; additional NB software with NB PHY/MAC are also required. This adds to the whole NBA MMS solution cost, design complexity, effort in interoperability tests and integration, especially for automotive-grade chipsets that must meet strict reliability requirements.

3.2 UWB-Driven MMS UWB

3.2.1 Overview of UWB-Driven MMS UWB

UWB-driven MMS UWB operates entirely within the HRP UWB PHY, using only UWB channels for control, ranging, and report phases. The initialization phase is still carried over BLE connection.

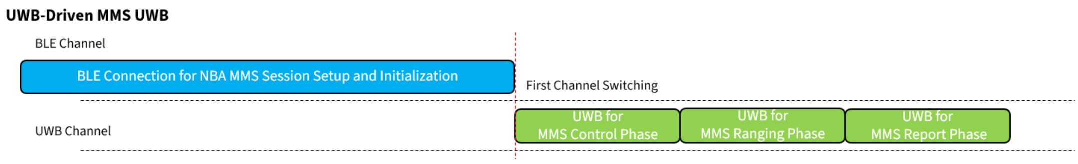

Figure 22: UWB-Driven MMS UWB

- Control and Report Phases: No external narrowband link is required, compact frames in control and report phases are all exchanged over the UWB channel. However, the session setup procedure still requires the NB or BLE link.
- MMS Ranging Phase: The initiator and responder exchange MMS ranging fragments consisting of multiple RSFs and/or RIFs in separate milliseconds, leveraging the per-millisecond regulatory transmit power budget.
- Synchronization: The first MMS ranging fragment includes SYNC and SFD to align timings of devices.
- Link Budget: Limited by the link budget of compact frame transmission over HRP UWB PHY in control and report phases

3.2.2 Major Advantages and Challenge for UWB-Driven MMS UWB

Major advantages include:

- No NB Spectrum Dependency: Avoiding the policy uncertainty and complexity of coexistence with 5.8 GHz and 6.2 GHz NB channels.
- Simpler System Design: Eliminating the need for an additional NB O-QPSK PHY, reducing the MMS UWB solution cost and integration complexity.

Major challenges include:

- Link Budget Constraints in Control and Report Phases: In typical test cases, UWB-driven MMS UWB achieves lower total link budget than that of NBA MMS UWB or OOB MMS UWB due to the link budget limitation of UWB channels running the control and report phases, especially in obstructed or long-range conditions.

- Time Synchronization: Unlike NBA MMS, there is no OOB assist to establish synchronization between devices in challenging RF conditions. The time synchronization sensitivity requires precise timing acquisition over the UWB channel alone and loss of synchronization can cause a forced session restart.

3.3 Out-of-Band (OOB) MMS UWB

3.3.1 Overview of OOB MMS UWB

Out-of-band (OOB) MMS UWB refers to using a non-IEEE 802.15.4 technology to handle the control and report phases, while still performing the UWB MMS ranging phase with UWB channel. In practice, the most common OOB candidate is Bluetooth Low Energy (BLE) [4], since almost all mobile devices support BLE and it has an excellent existing ecosystem for device discovery and communication.

Figure 23: OOB (BLE-Assisted) MMS UWB

In the BLE-assisted MMS mode, the devices use BLE connection to do MMS parameter negotiation and to trigger the UWB MMS ranging exchange, then report the results back over BLE connection as well. This approach is functionally similar to NBA MMS, but because BLE is not part of the IEEE 802.15.4 standard, it is not described in detail in the 802.15.4ab specification. However, it is an important implementation mode in practice, if we consider the exceptionally rich ecosystem of BLE, especially for smartphones and cars in the digital car key scenario.

3.3.2 BLE-Assisted MMS UWB Mechanism

Typically, in the BLE-assisted MMS UWB mode, the initiator will advertise over BLE connection to detect the presence of the responder(s). Once a BLE connection is established and an advertisement is captured, the two devices may exchange the necessary ranging session parameters over BLE connection. This could include:

- Management MAC configuration: slot, round, and block configurations for control, ranging, and report phases

- Management PHY configuration: PHY configuration of channels (NB or UWB channels), modulation, and data rate to be used for control and report phases

- Ranging PHY configuration: PHY configuration of UWB channels to be used for ranging phase,

- Number of MMS fragments: Numbers of MMS fragments (RSF/RIF) will be used in the ranging phase.

And the initiator will indicate the start time of the upcoming MMS ranging phase to the responder on the BLE connection as well.

At the appointed time, both initiator and responder devices enable their UWB radios and carry out the MMS ranging phase (similar to the above modes, with initiator sending MMS ranging fragments, etc.).

When the MMS ranging phase is done, both initiator and responder devices will enter the MMS report phase, where they switch off UWB and send the distance results or status information back to each other via BLE connections.

3.3.3 Key Advantages of BLE-Assisted MMS UWB

BLE is a mature wireless system and has an exceptionally rich ecosystem with robust support in smartphones and cars. It has built-in procedures for discovery, pairing, and secure communication. Leveraging BLE means developers can use existing libraries and ensure compatibility across vendors. Apart from these, the BLE-assisted MMS can provide more advantages:

- Full MMS Link Budget Gain:

  Achieving the complete MMS link budget improvement by allowing accumulation of multiple RSFs and RIFs, matching NBA MMS UWB performance in the ranging phase.

- No Additional Hardware Cost:

  Reusing existing BLE and UWB radios already present in most automotive and mobile platforms, without the need to add a dedicated narrowband hardware.

- No New Spectrum or LBT Requirement:

Operating control and report phases over the 2.4 GHz BLE band, avoiding the regulatory uncertainty and coexistence constraints of 5.8 GHz and 6.2 GHz NB channels, and eliminating the LBT overhead. Plus, the BLE spectrum is globally harmonized, simplifying worldwide deployment without region-specific NB spectrum policies.

3.3.4 Challenges for BLE-Assisted MMS UWB

For the BLE-assisted MMS UWB, the major challenge is time synchronization between initiator and responder devices. In order to achieve very good time synchronization before entering the MMS ranging phase, the BLE connection needs to help achieve time synchronization in the UWB domain, which may cause the following challenges:

- Automotive-Side Ecosystem Integration: In vehicles, BLE and UWB chipsets typically have independent clock sources, making it harder to maintain precise UWB time synchronization when control signaling is carried over BLE. This increases complexity in aligning timings of ranging fragments between initiator and responder.
- Time Synchronization Requirements: Requiring robust synchronization schemes to ensure that time synchronization information from BLE connection can translate into accurate UWB timing, especially in dynamic automotive RF conditions.

Fortunately, these challenges are not unsolvable. A promising BLE-assisted MMS solution will be detailed in Chapter 4.

3.4 Comparison of MMS UWB Modes

All the three MMS UWB modes use the same MMS UWB ranging idea—accumulating RSFs and RIFs across milliseconds to leverage per-millisecond power budget and boost sensitivity—but they differ in how the control and report phases are carried and what spectrum and hardware they rely on. The table below focuses on the differences and deployment considerations for these three modes.

Dimension	BLE-Assisted MMS UWB	UWB-Driven MMS UWB	NBA MMS UWB
Control and Report Phases	Offloaded to BLE	Via native UWB channel	Offloaded to NB O-QPSK
MMS Gain of Ranging Phase	Full MMS gain via RSF and RIF accumulation (same as NBA MMS)	Limited by control/report phase	Full MMS gain via RSF and RIF accumulation

Link Budget of Control and Report Phases	Good with BLE connection	Using UWB channel; bottleneck for data/SP0 transmission	Good with NB connection
Spectrum and LBT	- No new spectrum - No NB LBT - Operating on 2.4 GHz BLE	Using UWB spectrum only	- Using 5.8/6.2 GHz - LBT (e.g. CCA-based) before each NB TX, skipped if busy
Hardware / BOM	- No extra NB RF - Reusing BLE + UWB connection combo	- No extra NB RF - Reusing BLE + UWB connection combo	Requiring NB, which adds hardware, software, interoperability, etc.
Time Sync and Clocks	- Vehicles: BLE and UWB often on independent clocks, which needs robust time transfer - phones usually share a clock domain.	- Time sync entirely over UWB - SYNC+SFD as the first fragment	Pre-condition: NB and UWB sharing the same clock
Ecosystem Dependency	Low (BLE band globally harmonized)	Low (no NB dependency)	High (NB ecosystem needs to be built up from nothing)

Table 2: Comparison of MMS UWB Modes

4. BLE-Assisted MMS Solution

4.1 Overview of BLE-Assisted MMS Solution

Calterah's BLE-assisted MMS solution integrates Bluetooth Low Energy [4] with MMS UWB operation of IEEE 802.15.4ab (in progress) to realize the full link-budget gain of MMS without introducing a separate narrowband (NB) radio system. The architectural principle is straightforward: offloading MMS initialization, control, and report of compact-frame content to the BLE link, and dedicating the UWB channel exclusively to MMS ranging fragments (SYNC+SFD, RIFs, RSFs). This removes the transmission bottleneck of HRP UWB PHY for UWB-driven MMS and enables earlier ecosystem adoption than that of NBA MMS.

Compared with the current CCC Digital Key 3.0 and 4.0 solutions [3], the BLE-assisted MMS solution leverages BLE SoCs widely available on phones and vehicles, and reduces incremental system cost and solution complexity for implementing MMS UWB operation. Furthermore, BLE-assisted MMS is expected to share most higher-layer procedures with the current CCC Digital Key 3.0 and 4.0 [3] implementations using existing BLE connection.

Based on these characteristics mentioned, the BLE-assisted MMS solution will significantly accelerate the commercialization and large-scale deployment of MMS technology, and enable shorter time-to-market and smoother adoption of the MMS technology across automotive and IoT applications.

Test results from early implementations of Calterah's IEEE 802.15.4ab-compliant Dubhe UWB chips [5] show that, in the BLE-assisted MMS mode, a reliable ranging distance beyond 400 meters can be reached, dramatically extending the range supported by IEEE 802.15.4z operation. This improvement corresponds to an additional 20 dB link budget gain (the full MMS link budget gain as in NBA MMS), which enables stable non-line-of-sight (NLoS) ranging even through substantial obstructions.

Furthermore, according to the test results of Calterah's Dubhe UWB chips[5] in an underground parking lot, MMS UWB signals could penetrate five parked cars and still maintain a stable ranging exchange, ensuring the car can be securely unlocked even when the line of sight is blocked by other vehicles.

MMS UWB can also benefit ranging in the back pocket mode, where a digital car key is in a back pocket or backpack. The test results of Calterah's Dubhe UWB chips [5] in the back pocket mode show much more stable ranging compared to that of IEEE 802.15.4z operation.

4.2 System Architecture and Time Synchronization

In order to implement a BLE-assisted MMS solution in the automotive digital key application, the following system architecture may be adopted:

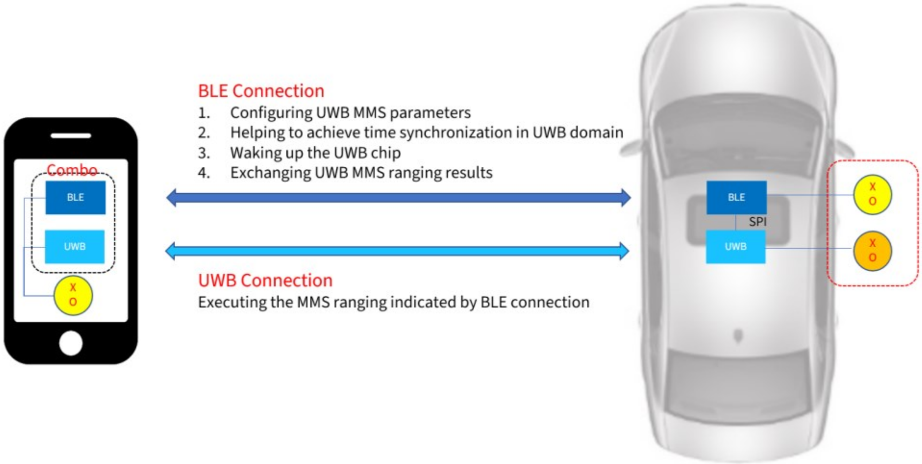

Figure 24: System Architecture of BLE-Assisted MMS

Roles

- Mobile Device : Equipped with a combo of a BLE SoC and a UWB SoC, usually with the same clock source

- Vehicle: Equipped with a BLE SoC and a UWB SoC with shared or separate clock source

- BLE SoC: Maintaining a secure BLE connection, in order to set up an MMS session, transport MMS control and report content (compact frames), and assist UWB time domain synchronization.

- UWB SoC (IEEE 802.15.4ab): Executing the MMS ranging phase by exchanging SYNC+SFD fragment (optional), RIFs, and RSFs in the UWB domain only.

Interfaces Between BLE SoC and UWB SoC (Vehicle Side):

- SPI/UART: For offloading data packets of the initialization, control, and report phases to the BLE SoC

- Timer-controlled GPIO: Used for precise UWB timing synchronization indication from the BLE SoC and transmission of BLE time synchronization information or CFO estimation information from the BLE SoC to the UWB SoC.

- A shared XO (optional): Providing the same clock source for the BLE SoC and the UWB SoC

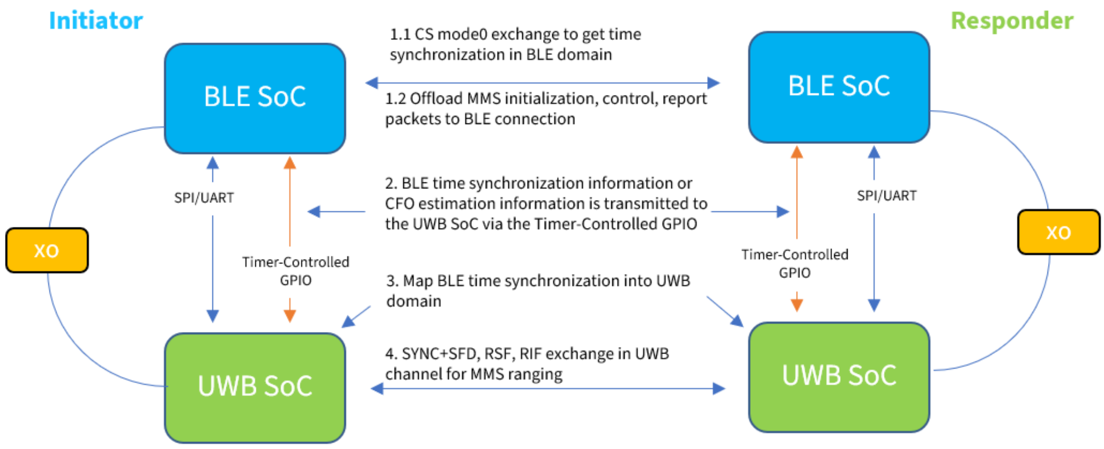

Figure 25: System Functions of *BLE-Assisted MMS*

Major Functions

BLE SoC

- The BLE connection enables major transmission functions between the mobile device and the vehicle:
  - CS mode-0 exchange to get time synchronization in the BLE domain (optional)
  - Offloading MMS initialization, control, and report packets to BLE connection

UWB SoC:

- Getting the BLE time synchronization information or CFO estimation information and mapping BLE time synchronization into the UWB domain
- Performing MMS-based ranging by exchanges of multiple SYNC+SFD fragments (optional), RSFs, and RIFs

Time Synchronization in UWB Domain

In the BLE-assisted MMS solution, BLE connection carries data transmission for initialization, control, and report phases while UWB performs fine-timed MMS ranging. When the UWB connection is woken up by BLE connection, the fine time synchronization shall be achieved in the UWB domain between the mobile device and the vehicle. Otherwise, CIR estimation and accumulation by exchanging MMS fragments will be degraded.

Depending on the practical implementation, two possible ways are available to get time synchronization in the UWB domain.

- For the case that a BLE SoC and a UWB SoC share one clock source in both the mobile device and the vehicle side:
  - Fine time synchronization (at the ns level) mapping can be achieved between the BLE time domain and the UWB time domain
  - Achieving fine time synchronization in the BLE domain between the mobile device and the vehicle side (e.g., by using the Channel Sounding Mode-0 procedure)
  - Mapping fine time synchronization in the BLE domain to the UWB domain
- For the case that a BLE SoC and a UWB SoC have separated clock sources in either the mobile device or the vehicle side:
  - Coarse time synchronization (at the ms level) mapping can be achieved between the BLE time domain and the UWB time domain. (e.g., UWB domain timing associated with the same BLE ACL connection timing)
  - Fine time synchronization in the UWB domain (at the ns level) can be achieved by using the first SYNC+SFD UWB fragment exchange in the MMS ranging phase

4.3 Procedure and Message Mapping

In the BLE-assisted MMS solution, a secure BLE connection carries all control-plane traffic: session setup, MMS initialization, control, time synchronization assisted information for the UWB domain, wakeup triggers or hand-over triggers, and post-ranging results transmission.

The UWB channel is reserved exclusively for the MMS ranging phase, where the SYNC+SFD fragment, RSFs, RIFs are exchanged with tight timing. After the UWB MMS fragment window completes, both the mobile device and the vehicle switch back to BLE connection to deliver the measurement report.

The procedure overview of BLE-assisted MMS is shown below:

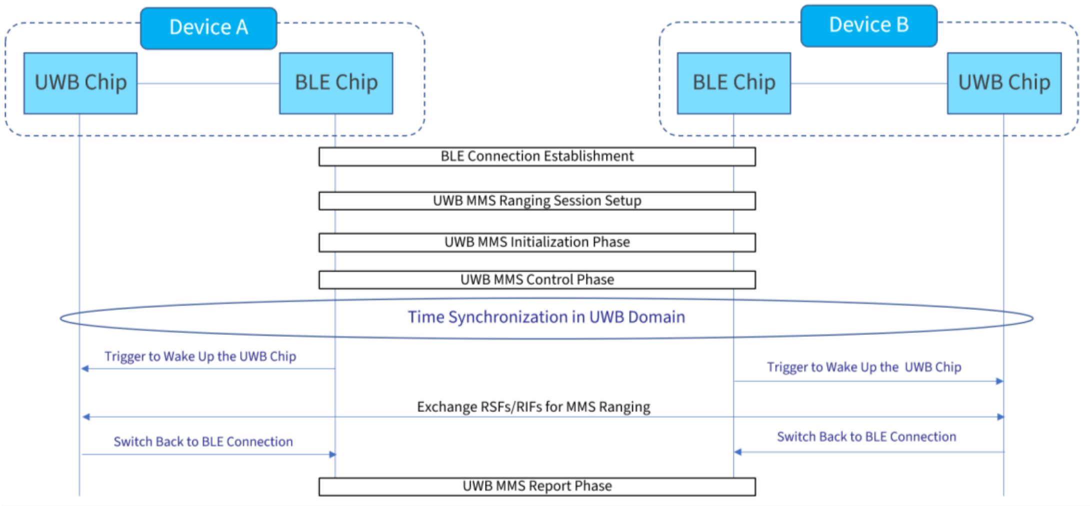

Figure 26: Message Flow of BLE-Assisted MMS

A detailed description of the flow is as follows:

(1) BLE Connection Establishment

Devices A and B establish an encrypted BLE link. This link is the transport for all MMS control messages and the results reported later.

(2) UWB MMS Ranging Session Setup (over BLE connection)

The initiator and responder negotiate the MMS session configurations on BLE connection, including MMS ranging block configuration, MMS fragment configuration, the UWB channel, and other session parameters.

(3) UWB MMS Initialization Phase (over BLE connection)

The MMS initialization message (compact frame) is encapsulated in BLE messages. This prepares both sides for the upcoming MMS control, ranging, and report phases.

(4) UWB MMS Control Phase (over BLE connection)

MMS control phase message (compact frame) is encapsulated in the BLE message.

(5) Time Synchronization in the UWB Domain

- Depending on the clock source options, getting time synchronization in the BLE domain (e.g., using CS mode-0 procedure), or by using the UWB time reference to align with the timing of the same BLE ACL connection.

- Apply the time synchronization mapping between the BLE domain and the UWB domain, so that both devices align their local UWB time base and share the same reference for the upcoming ranging phase (at the ns level).

(6) Trigger to Wake Up the UWB Chip

Each BLE chip triggers to wake up its local UWB chip for the upcoming MMS ranging phase.

(7) Exchanging SYNC+SFD (Optional), RSFs, and RIFs for MMS Ranging

SYNC+SFD (optional), RSFs, and RIFs are transmitted and then received via the dedicated UWB channel. BLE connection remains quiet except for local coordination.

(8) Switching Back to BLE Connection

When the UWB MMS ranging phase finishes, both devices return to the BLE link.

(9) UWB MMS Report Phase (over BLE connection)

MMS ranging results and related statistics are encapsulated in the BLE message and exchanged over BLE connection, which concludes the round or prepares for the next one.

4.4 Integration with BLE Channel Sounding

4.4.1 Principle of BLE Channel Sounding

Bluetooth Low Energy (BLE) Channel Sounding (CS) [4], introduced in the Bluetooth 6.0 specification, enables devices to estimate distance by transmitting and receiving well-defined CS signals over multiple CS channels. Both Phase-Based Ranging (PBR) and Round-Trip Timing (RTT) are supported in BLE CS. Unlike traditional BLE RSSI-based ranging, CS leverages phase difference and time of flight (ToF) between transmitting and receiving CS signals, which significantly improves ranging accuracy and resilience against multipath interference.

BLE CS ranging typically achieves accuracy at the level of tens of centimeters under line-of-sight conditions. However, compared with UWB, which operates over hundreds of MHz and provides <10 cm accuracy, BLE CS is inherently limited in resolution due to its narrower effective bandwidth. BLE CS can offer device discovery capability, coarse distance estimation, time synchronization assistance in the UWB domain, making it highly complementary to UWB MMS systems.

4.4.2 BLE CS for UWB Time Synchronization in BLE-Assisted MMS Solution

In the BLE-assisted MMS UWB solution, BLE CS can be used not only for its own ranging capability but also as time synchronization assistance between initiator and responder devices in the UWB domain. By establishing fine time alignment in the BLE domain using BLE CS mode-0 and then mapping this synchronization information to the UWB domain, the devices can align the MMS fragment boundaries (MMS ranging slots) more accurately in MMS ranging fragments exchanges. This approach reduces the need for complex blind synchronization in UWB alone and the additional requirement of tightly-coupled NB O-QPSK PHY, and ensures that CIR accumulation across fragments remains coherent.

4.4.3 Relationship Between BLE CS and MMS UWB

BLE CS and MMS UWB ranging are not competing technologies but rather complementary layers of a hybrid ranging system. BLE CS provides fast device discovery, coarse distance estimation, and time synchronization, while MMS UWB delivers high-accuracy, highly reliable, and long-range measurements.

In scenarios where both technologies are deployed, for example, in the use case of automotive digital key, this complementarity becomes especially valuable:

- BLE CS for proximity detection and wakeup: BLE CS can be used as the first stage to detect when a smartphone or fob is within a few meters of the vehicle. It quickly provides a coarse distance estimate and assists in aligning UWB timing, allowing the vehicle to wake up its UWB chip only when needed, reducing power consumption.

- MMS UWB for secure fine ranging: Once BLE CS confirms proximity and synchronizes timing, MMS UWB is activated to perform long-distance, high-accuracy, highly reliable ranging. MMS provides the robustness against body blockage, multipath, and non-line-of-sight conditions that BLE alone cannot achieve, ensuring precise unlock decisions and protection against relay attacks.

- Combined decision logic: BLE CS ensures detection and energy efficiency, while MMS UWB ensures security and precision. Together, they enable a multi-layer decision-making ranging framework.

Thus, in automotive digital key systems, the integration of BLE CS and MMS UWB allows manufacturers to combine the ecosystem ubiquity of BLE with the precision and robustness of UWB MMS, leading to a more seamless, secure, and user-friendly passive entry experience.

5. Conclusion

The introduction of Multi-Millisecond (MMS) UWB operation in IEEE 802.15.4ab (in progress) represents a significant advancement in the UWB ranging technology, directly addressing the limitations of range and reliability issues that the current UWB ranging systems are facing. By extending the UWB ranging exchange over multiple milliseconds and intelligently boosting and accumulating UWB ranging energy, MMS UWB achieves dramatically improved link budget and multipath resilience compared with the current UWB ranging scheme. This enables UWB ranging systems to be adopted in new use cases, especially in long-distance secure passive entry for vehicles.

Three distinct operational modes give implementers the flexibility to choose a strategy that best fits the hardware capabilities of their products and use case requirements.

- NBA MMS UWB: A narrowband O-QPSK PHY at 5.8 GHz or 6.2 GHz carries MMS packets for UWB initialization, control, and report, while UWB carries the MMS ranging fragments.
  - NB transmissions are subject to LBT (e.g. CCA-based) before each TX;
  - NBA MMS UWB can deliver the full MMS ranging gain with a very robust control and report transmission over NB connection.
  - NBA MMS UWB requires additional cost, for hardware, software, and interoperability etc. of NB.
- UWB-driven MMS UWB: All MMS UWB phases—control, ranging, report—run purely on UWB.
  - Time synchronization is established with SYNC+SFD and the RSFs and RIFs of the MMS packet are exchanged and accumulated across milliseconds.
  - UWB-driven MMS UWB does not depend on NB, without channel switching
  - UWB-driven MMS UWB cannot deliver the full MMS ranging gain, due to the limitation of the link budget of the control and report phases running on the UWB channel.

- OOB MMS (BLE-assisted MMS) UWB: BLE connection carries setup, control, and reporting of the MMS UWB session, while UWB carries the MMS ranging fragments (SYNC+SFD, RSFs, and RIFs)
    - OOB MMS can deliver the full MMS ranging gain with very robust transmission of control and report over BLE connection.
    - No new spectrum or LBT (e.g. CCA-based) mechanism is needed
    - An exceptionally rich ecosystem without the additional hardware cost based on the current digital car key system
    - Appropriate mechanism needed to address time and frequency synchronization between devices in the UWB time domain

As of 2025, IEEE 802.15.4ab (in progress) is still in the draft stage, but its core features like MMS UWB operation are already solid and implemented by leading semiconductor companies. The integration of IEEE 802.15.4ab (in progress) into industry consortium specifications (CCC) is initiated. We can expect the MMS UWB technique to become a game changer for next-generation UWB applications, enabling scenarios like "Finding My Car" with a phone, high-precision asset tracking, or new applications—all with the confidence that the underlying ranging is robust and accurate even at long distances.

In conclusion, MMS UWB operation extends the UWB ranging capability to become more precise and reliable in the real world, in a large-scale deployment. This white paper provides a deep dive into the MMS principles and MMS modes of operation, serving as a guide for those who aim to leverage MMS UWB in their own wireless systems. With this knowledge, engineers can better architect solutions that meet the ever-growing demand for distance-aware connectivity across smart vehicles, homes, and industrial environments.

References

[1] IEEE 802.15.4z-2020 IEEE Standard for Low-Rate Wireless Networks--Amendment 1: Enhanced Ultra Wideband (UWB) Physical Layers (PHYs) and Associated Ranging Techniques, 2020

[2] IEEE P802.15.4ab/D02 IEEE Draft Standard for Low-Rate Wireless Network Amendment 1: Enhanced Ultra Wide-Band (UWB) Physical Layers (PHYs) and Associated Medium Access and Control (MAC) sublayer Enhancements, Mar 2025

[3] Car Connectivity Consortium Digital Key Technical Specification Version 4.0.0, 2025

[4] Bluetooth Core Specification Version v6.0, 2024

[5] Calterah Dubhe UWB SoCs, Accessed: https://www.calterah.com/en/company-news-detail/367

Abbreviations

Abbreviation	Term
ACL	asynchronous connection-less
ARDEV	advanced ranging device
BLE	Bluetooth Low Energy
BPM	burst position modulation
BPSK	binary phase shift keying
CIR	channel impulse response
CS	channel sounding
EIRP	effective isotropic radiated power
ETC	electronic toll collection
HRP	high-rate pulse repetition
LBT	Listen Before Talk
LoS	line of sight
MAC	media access control
MMRS	multi-millisecond ranging sequence
MMS	multi-millisecond
NBA	narrowband assisted
OOB	Out of Band
O-QPSK	Offset quadrature phase-shift keying
RIF	ranging integrity fragment
RSF	ranging sequence fragment
RSSI	Received Signal Strength Indicator
RSTU	ranging scheduling time unit
SIG	Special Interest Group
ToF	time of flight
UNII	Unlicensed National Information Infrastructure
UWB	ultra-wideband
V2X	Vehicle-to-Everything

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