A Survey on 5G NR Sub-band Full Duplex

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***Abstract*—Sub-band Full Duplex (SBFD) has garnered significant attention in both industry and academia as a promising solution to the pressing challenges of maximizing spectral efficiency and overcoming limitations in dynamic resource operation for next-generation wireless communications. This paper surveys SBFD-related standardization activities in 3GPP Release 18 and Release 19, summarizing key procedures for practical deployment, including enhanced transmission and reception operations, SBFD-aware random access, and cross-link interference (CLI) measurement and reporting mechanisms. This study demonstrates that SBFD has progressed from a conceptual proposal into a practical technology ready for commercial deployment and outlines future directions for its standardization and development.**

***Index Terms*—Subband Full Duplex, 5G NR, Random Access, Cross Link Interference**

I. Introduction

5G NR (New Radio) duplex refers to how 5G networks handle bidirectional communication, essentially how they manage the simultaneous transmission and reception of data between base stations and devices [1].

To provide the highest possible flexibility, 5G NR supports various duplexing schemes such as Frequency Division Duplex (FDD), Time Division Duplex (TDD), Semi-static TDD, and Dynamic TDD [1], [2]. Wireless systems have traditionally used two main duplexing methods, FDD and TDD, as illustrated in Fig.1. FDD enables two-way communication simultaneously using different frequency bands for uplink and downlink transmission, whereas TDD operates on one frequency band alternating time slots between uplink and downlink transmissions but requires accurate synchronization and faces interference problems in dense deployments [1].

The 5G NR duplexing framework continues to evolve as demands for spectral efficiency and dynamic traffic adaptation increase. It includes advanced TDD enhancements such as flexible slot configurations and adaptive scheduling. Sub-band Full Duplex (SBFD), a technique that enables simultaneous uplink and downlink transmissions on separate subbands within the same TDD carrier, as illustrated in Fig.2; has progressed beyond initial study and is now under active standardization in 3GPP Release 19 [3]. This evolving framework supports the exploration of SBFD as a key innovation addressing the limitations of conventional TDD and FDD, aligning with the needs of 5G-Advanced and emerging 6G systems [3].

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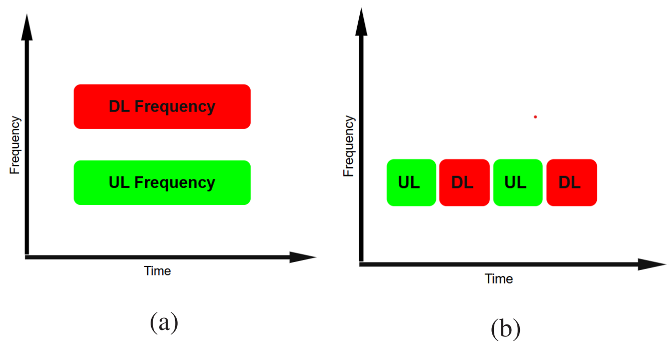

Fig. 1. Traditional duplex schemes: (a)FDD; (b)TDD

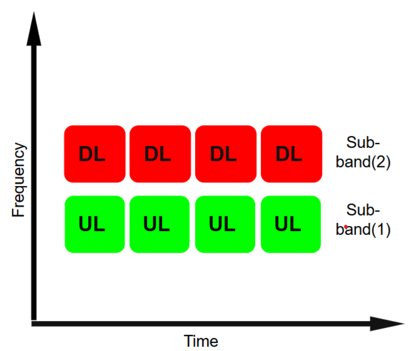

Fig. 2. SBFD

SBFD is driven by the need for better spectrum efficiency, lower latency, and smoother coexistence with legacy systems [4]. By enabling simultaneous uplink and downlink on different subbands within the same carrier bandwidth, SBFD maximizes spectrum utilization and reduces communication delays. Its flexible design also allows coexistence with traditional duplexing schemes, supporting a gradual evolution of network infrastructure [3].

This paper surveys the development path of SBFD within the 5G NR duplexing framework, covering its transition from feasibility study in Release 18 to formal specification work in Release 19 [3], [4]. It reviews SBFD slot structures, guardband principles, and Cross Link interference(CLI)-metric proposals introduced in Release 18 feasibility study [4]. In Release 19, SBFD became an official work item, with discussions focusing on measurement/reporting procedures, as well as interference mitigation techniques [3]. This survey draws primarily on 3GPP RAN1 contributions and meeting reports, with supplementary insights from RAN2/RAN4 and selected papers [1], [2]. Performance results are referenced from standardized 3GPP evaluation scenarios to provide an objective overview of SBFD's technical progression and standardization challenges [4].

II. Evolution of NR Duplex Operation

A. SBFD Baseline Operating Model

3GPP Release 18 formalizes a single, semi-static SBFD framework [4]. Every SBFD symbol carries exactly one pre-signalled downlink (DL) sub-band and one uplink (UL) sub-band; their Common Resource Block (CRB)-relative start and size are broadcast through Radio Resource Control (RRC) along with the list of symbol indices that constitute the SBFD pattern [4]. SBFD-aware UEs may transmit only inside the configured UL sub-band and may receive only inside the DL sub-band(s), whereas legacy UEs continue to interpret the slot according to the ordinary TDD map [4]. The baseline confines SBFD to a single DL/UL Bandwidth Part (BWP) pair with co-centered carriers and allows at most one UL sub-band per SBFD symbol, an assumption jointly endorsed by RAN4 [5].

B. Reference Slot–Frequency Patterns

All Release 18 evaluations employ two canonical frequency layouts [6]. In the *center-UL* pattern $\{D\,U\,D\}$ a 20-MHz UL sub-band sits between two 40-MHz DL sub-bands inside a 100-MHz carrier, while the *edge-UL* pattern $\{D\,U\}$ places the UL sub-band at one spectrum edge (80 : 20 MHz split in FR1). These patterns scale proportionally with carrier bandwidth and eliminate ambiguity when companies compare results.

C. Interference and Antenna Assumptions

Self-interference (SI) is assumed to stay the same across the UL band. It is set so that it does not reduce the UL receiver's performance by more than 1 dB [4]. For co-site CLI, FR1 simulations cover three isolation levels: 75 dB (typical), 93 dB (best) and 100 dB (exploratory); FR2 adopts 88 / 98 / 105 dB [5]. Three RF front-end options are permitted:
(i) Same aperture and TxRUs as legacy,
(ii) Twice the antenna aperture with the same TxRUs, and
(iii) Same aperture with half the TxRUs. [7].

D. Evaluation Framework and Metrics

Release 18 system-level and link-level studies share a harmonised test bench [6]. Traffic follows the File transfer Protocol (FTP-3) model; Indoor-Office, Urban-Macro and Dense-Urban deployments adopt common UE densities, mobility (3 km/h pedestrian, 30 km/h vehicular) and indoor/outdoor splits. Key performance indicators include mean, median, 5th- and 95th-percentile user throughput, packet-latency CDF, and link-budget metrics; maximum path-loss, coupling-loss and implementation-loss for four UL-coverage modes (Type-A repetition and Transmit Beam-based Uplink Multiple SRS, each with and without joint channel estimation) [6]. When SBFD is disabled, dynamic-TDD baselines are re-simulated under identical traffic and guard-symbol rules to provide apples-to-apples comparisons [7].

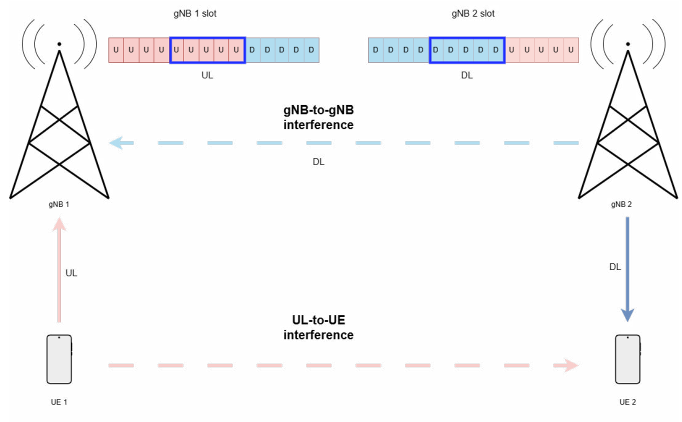

Fig. 3. Cross Link Interference

E. Causes and Solutions of CLI

CLI is cross-link interference that generally occurs when both uplink and downlink transmissions are required on the same resource between users or cells. This type of interference negatively affects the transmission and reception of both gNBs and UEs, and it is broadly classified into two types: gNB-to-gNB CLI and UE-to-UE CLI. [4] In the gNB-to-gNB scenario, CLI is mitigated through uplink muting, while in the UE-to-UE scenario, CLI is mitigated through measurement and reporting procedures.

III. Key Technical Areas

This section explains how the Release 19 work turns SBFD from a feasibility study into a usable feature [3].

A. Tx/Rx/Measurement Procedures Enhancements

The Release 19 specifications refine core transmission, reception, and measurement rules so that SBFD-aware and legacy UEs can share spectrum seamlessly while the gNB retains deterministic control of resources [8].

- **Semi-static sub-band indication**
  Release 19 confirms that SBFD time- and frequency-domain locations are broadcast on a cell-specific basis: each TDD pattern carries one start/stop slot index, and up to two DL sub-bands plus one UL sub-band may be configured per Subcarrier Spacing(SCS). UE-specific overrides are intentionally out of scope, so every SBFD-aware terminal derives its symbol set and Resource Block(RB) windows directly from the cell-level RRC message, ensuring all devices schedule on the same fixed SBFD grid [8].

- **Determination of UL/DL usable Physical Resource Blocks(PRBs)**
For each active BWP, the UE computes *UL-usable PRBs* as the intersection of the configured UL sub-band with that BWP, and *DL-usable PRBs* likewise from each configured DL sub-band; no explicit list is signalled. This Option-1 rule applies whenever the network foregoes any UE-specific sub-band definition, providing a deterministic and signalling-free way to delimit usable spectrum inside SBFD symbols [8].

- **UE behaviour inside SBFD symbols (single-slot scope)**
Within a slot marked SBFD, the terminal may transmit only on UL-usable PRBs and may receive only on DL-usable PRBs; any attempt to use resources outside those windows is barred, except when the UE performs CLI measurements on the downlink. Thus, ordinary UL payload never straddles a sub-band edge and ordinary DL payload never intrudes into the UL sub-band, preserving strict duplex separation inside each SBFD symbol [8].

- **Occasions that span SBFD and non-SBFD symbols (intra-slot collisions)**
If a physical-channel occasion mapped by legacy rules extends across the SBFD boundary within a single slot, the UE suppresses or truncates the occasion according to channel type: Physical Uplink Shared Channel (PUSCH) type-B repetitions are segmented at the boundary and any segment in the invalid symbol type is dropped, while repetition-type-A, A-SRS, and TBoMS occasions are postponed to the next valid slot; all other channels simply drop their overlapping instance [8].

- **UE behaviour across slots (Configuration 1 vs Configuration 2)**
Every BWP is tagged either Configuration 1, meaning all transmissions and receptions for that channel stay within a single symbol type or Configuration 2, which permits separate frequency resources for SBFD and non-SBFD slots [8]. Configuration 2 is optional and guarded by UE capability; when it is enabled, the gNB signals a single PRB set for non-SBFD slots and an RB offset for SBFD slots, keeping equal PRB counts while ensuring the SBFD allocation remains inside the UL-usable window [8].

- **Guard and transient periods between symbol types**
A fixed transmitter transient of $10\,\mu$s (FR1) or $3\,\mu$s (FR2-1) is reserved whenever the gNB switches between SBFD and non-SBFD operation [8]. The location of that guard depends on the direction change: DL$\rightarrow$UL transitions place the mute period at the start of the UL symbol, UL$\rightarrow$DL at the end of the SBFD symbol, and mixed DL/SBFD transitions may reserve either initial SBFD symbols or final non-SBFD DL symbols at gNB discretion [8]. No explicit guard-symbol signalling is required at the UE, consistent with the RAN4 Case-B guard-period definition [5].

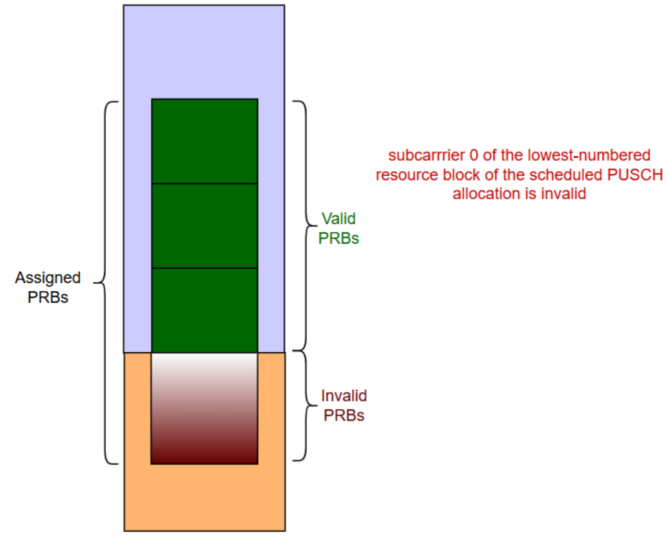

Fig. 4. Resource availability for DMRS Sequence Mapping

- **Frequency-domain allocation enhancements**
For RA-type 0/1 scheduling, the UE treats any Resource Block Groups(RBG) or Precoding Resource Group(PRG) that overlaps a sub-band edge as partially valid, using only the PRBs inside the usable window for demodulation and Transport Block Size(TBS) calculation; wide-band PRG and partial PRG are both supported subject to UE-capability limits, and DM-RS/CSI-RS sequences are simply punctured over invalid PRBs without redefining the mapping [6], [8]. When two DL sub-bands exist, a single contiguous CSI-RS resource may span them, with the processing timeline optionally doubled but CPU counting left unchanged [8].

- **Measurement procedures**
SBFD-aware UEs confine normal channel measurements to DL-usable PRBs but may sample outside those bands for CLI estimation using SRS-RSRP or CLI-RSSI resources [8], [9]. The network can request periodic, semi-persistent, or aperiodic reports of new quantities such as L1-SRS-RSRP and L1-CLI-RSSI, and prioritisation follows the existing CSI reporting rules defined in the NR physical-layer procedures [6], [8]. At least wide-band reporting is mandatory. No change is made to the core CSI framework measurement resources reuse legacy patterns, and the only timeline impact is the optional $\times 2$ extension when a CSI-RS spans both DL sub-bands [6], [8].

B. Random Access Operation

The Release 19 specifications extend the NR random-access procedure with SBFD-aware options; dual Random Access Channel (RACH) configurations, updated RO mapping, and power-control refinements, so that new and legacy UEs can enter the network on the same carrier without conflict [10].

- **RACH-configuration modes for SBFD-aware User Equipments (UEs)**
  Release 19 supports two mutually exclusive configuration options [10].
  Option 1 keeps a single `rach-ConfigCommon`; the network simply "validates" any random-access occasions (ROs) that fall inside uplink SBFD symbols, and the UE treats every other aspect of RACH exactly as in legacy NR, re-using the unpaired-spectrum tables of [2], [10].
  Option 2 creates a second configuration, `sbfd-RACHDualConfig`, that governs only ROs in SBFD symbols, while the legacy configuration continues to serve non-SBFD symbols; the UE is never expected to run both options simultaneously [10].

- **RO validation, Synchronization Signal Block (SSB)-to-RO mapping and guard-time rules**
  Under Option 1 the legacy SSB-to-RO mapping, defined in [2], remains in force for ROs located in uplink or flexible symbols, whereas ROs inserted into SBFD downlink symbols rely on a separate mapping so that no downlink traffic overlaps with Physical Random Access Channel (PRACH) receptions [2], [10].
  Option 2 applies the same principle through the additional `sbfd-RACHDualConfig`; it may simply declare any RO positioned in a non-SBFD symbol invalid (Alt 2-3) [10].
  In either case, a candidate RO must start at least N_{gap} symbols after the last downlink or SSB symbol; if an RO spans an SBFD/non-SBFD boundary, one guard symbol is reserved before the first pure-uplink symbol, in line with the RAN4 Case-B guard-period definition [5].

- **PRACH repetition and RO-type selection strategy**
  A UE repeats a preamble only within the same RO type; cross-type repetition is not included in the Release 19 SBFD baseline [10]. For the initial preamble, it may follow network-configured priorities or choose freely, but once a type is selected the UE either stays on that type or switches after a configured number of failures. These behaviours, specified in the SBFD random-access agreement and aligned with the generic PRACH rules of [11], apply to both RACH options and give operators latitude without introducing new physical-layer signalling [3], [10].

- **Power-ramping behaviour across RO types**
  There is a single power-ramping counter maintained per RA procedure; whenever the UE changes RO type legacy to additional or additional to legacy, it increments that counter without reset or offset compensation, irrespective of the selected RACH option [10]. The Medium Access Control (MAC) layer always forwards the resulting $\Delta P_{\text{rampup\_requested,b,f,c}}$ to Layer-1 as "the ramp applied to the most recent preamble," following the generic power-ramping rules defined in [3]; therefore, the PHY does not need to track separate histories.

- **Msg3 frequency-domain resource allocation in SBFD symbols**
  For Msg3 scheduled inside an SBFD symbol, the gNB reuses the legacy Frequency Domain Resource Allocation (FDRA) procedure in [3]. The only modification is the reference span: hop-2 offsets are computed relative to the UL PRBs that lie inside both the active UL-BWP and the configured UL sub-band, rather than the entire BWP, as specified in the Release 19 SBFD random-access baseline [10]. No extra bits, truncation rules, or separate initial UL-BWP are introduced because the plenary chose the "no enhancement" alternative (Alt 2) [10].

- **Msg3 and Physical Uplink Control Channel (PUCCH) power-control parameters**
  When separate values are configured, `preamble-ReceivedTargetPower`, `p0-nominal-sbfd`, and `msg3-Alpha-sbfd` apply only to transmissions in SBFD symbols; otherwise, the legacy values are reused seamlessly. For both RACH options, the gNB derives Msg3 power from the `preambleReceivedTargetPower` that corresponds to the RO type of the preamble, legacy for non-SBFD symbols, additional for SBFD symbols following the generic power-control formulae in [3]. No new `msg3-DeltaPreamble-SBFD` field was adopted, so the existing offset continues to govern all Msg3 occasions [10].

- **Additional RACH parameter set under Option 2**
  `sbfd-RACHDualConfig` may include every field of `rach-ConfigCommon` except `rsrp-ThresholdSSB-SUL`; any omitted field is inherited from the legacy configuration, giving maximum flexibility while avoiding redundant signalling when legacy and additional RACH share identical values [10].

- **Legacy-RO behaviour guarantee**
  To retain backward compatibility, a UE that begins contention-based random access in a legacy RO performs the full four-step procedure exactly as defined for Release-15 NR, even if it later receives an SBFD configuration. No SBFD-specific constraints or power corrections are applied, ensuring that SBFD-capable and legacy terminals can coexist in the same cell without modification [3], [10].

C. CLI Handling Techniques

The Release 19 CLI-handling package defines how SBFD cells measure, report and actively suppress cross-link interference, adding dedicated SRS-/RSSI-based measurement resources, compact UCI reporting formats, and a standards-controlled UL-muting mechanism that can be invoked per-UE and per-PUSCH to protect downlink reception in both SBFD and legacy TDD deployments [9], [12].

- **Configuring CLI Measurement Resources**
  The CLI measurement resource refers to a time-frequency region that a UE is scheduled to capture a cross-link-interference signal. The `CSI-ResourceConfig` setting of the RRC layer is extended so that it can be configured as a measurement-resource set for SRS-RSRP and CLI-RSSI methods [12]. Each CLI measurement-resource set may be periodic or aperiodic, mirroring the options available for CSI-RS resources in [13]. The periodic and semi-persistent measurement sets configured per `CSI-ResourceConfig` are limited to a maximum of one each, matching the CSI-RS resource restriction. Accordingly, UE implementation is simplified and the existing CSI-RS configuration structure is reused.

- **CLI Measurement Resource Set**
  The *SRS-RSRP* measurement resource captures a SRS transmitted by another UE and measures its received-signal power (RSRP). This value indicates the interference intensity that a neighbouring UL transmission imposes on a victim UE's DL reception. By contrast, CLI-RSSI measures the instantaneous received-signal strength (RSSI), that is the total power of signal + interference + thermal noise over the configured frequency resource without relying on a dedicated reference signal. In practice, SRS-RSRP is most useful when the interfering UE can be identified (for example, it periodically transmits SRS), whereas CLI-RSSI provides a broader indication of the ambient interference environment.

- **QCL type-D**
  An important part of setting the CLI measurement resource is the utilization of the Quasi Co-Location(QCL) type-D assumption, and since the interference signal will be received in a spatially specific direction, it is premised that the measurement beams of the UE are properly aligned. In RAN1, in order to provide beam information on the interference source for each CLI measurement resource, it is decided to introduce a higher layer parameter capable of specifying a Transmission Configuration Indicator (TCI) state and a QCL type-D for each periodic CLI measurement resource [14]. That is, each CLI measurement resource may be configured to have a type-D QCL relationship from a certain reference signal, and the UE may know the beam direction to receive the interference signal in advance.

- **Semi-persistent Case CLI Measurement Method**
  Even in the case of semi-persistent (SP) CLI measurement resources, activation/inactivation may be controlled through a MAC Control Element (CE) method configured in advance in the upper layer RRC [9]. Specifically, an SP CLI measurement resource set active/inactive MAC CE is newly defined, and thus the base station may specifically instruct the UE to use a specific semi-persistent resource [9].This definition allows the MAC CE to include a TCI state ID field for beam designation of the corresponding measurement resource, so that the UE may recognize the interference measurement beam even in dynamic activation [8], [9].

- **CLI Measurement Reporting Format and Quantization**
  The CLI measurement value is reported through the existing uplink control information (UCI). At this time, the measurement resource set value {cli-RSSI, cli-SRS-RSRP} was added to the CLI report in the upper-layer parameter `reportQuality` [9] The contents and format of the CLI report can be summarized as follows [12].
  1) Number of reported resources M: The base station configures the number M of interference-measurement resources to report in the `CSI-ReportConfig` as 1, 2, 3, or 4.
  2) Measurement Resource Identifier (MRI) report
     UE sends the identifier (ID) of each CLI-measurement resource together to identify the M reported measurements and measurers.
  3) Absolute and Differential Value Reporting
     Adopt the method of reporting the most-interfering resource among M resources as an absolute measurement and the remaining resources as differences from that maximum [12].
     - Quantization bit count and range
       L1 SRS-RSRP value, L1 cli-RSSI value, and differential value are expressed in 7, 7, and 4 bits, respectively, with minimum steps of 1 dB, 1 dB, and 2 dB and ranges of (-100 dBm to -25 dBm), (-140 dBm to -44 dBm), and (0 dB to 30 dB) [12].
     - Differential Value-Based Interference Strength Interpretation
       A differential value of 0 denotes an interference source within 0 dB–2 dB of the reference. larger values indicate lower interference intensity [12].

- **Need for UL Resource Muting**
  Among the CLI-interference-mitigation techniques, the core method covered in the RAN1 specification is *uplink*

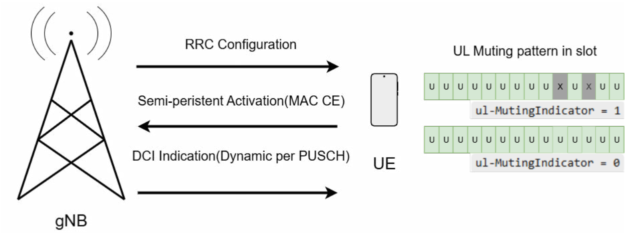

Fig. 5. Example of UL muting process when setting up 2 symbol mute per slot

resource muting, that is erasing selected UL-transmission resources. UL-resource muting reduces cross-interference by instructing the UE to intentionally leave some symbols or resources empty; the trade-off is less UL capacity in exchange for lower interference. In SBFD, muting some OFDM symbols of the transmitting UE allows the DL-receiving UE to decode without interference and improves performance [4], [9]. Similarly, when two adjacent cells operate dynamic TDD, muting the symbols that would create the greatest interference from the UL-side cell protects DL reception in the neighbouring cell [9].

- **Introduction of UL Mutation for SBFD, Legacy TDD Adjacent Operation**
  When SBFD and legacy TDD are operated adjacent to each other, interference from UL transmissions in SBFD cells can limit DL reception in neighbouring TDD cells; this degradation can be greatly mitigated by introducing UL muting . Therefore, the network must control which UEs apply muting to which PUSCH transmissions, and the mitigation effect is maximised only when it is applied consistently across multiple UEs. For this reason, the Release 19 standard defines detailed higher-layer signalling and physical-layer operation rules for UL muting [1], [9].

- **UL muting indication parameter**
  By adding a field called ul-MutingIndicator to a PUSCH-Allocation RRC configuration, a signal may transmit a predetermined UL-muting symbol pattern (=1) or not (=0) during a specific PUSCH transmission [9]. Because the indicator is included in the allocation infor-mation of the PUSCH transmission, the UE can deter-mine whether muting is applied to each UL transmission [9]. Even when multiple PUSCHs are simultaneously scheduled with a single Downlink Control Information (DCI) (e.g., multiple TB or multi-ple BWP situations), mutingIndicator may be applied to each PUSCH [9]. Figure 7 illustrates this process.

- **Setting the location of the Muting symbol**
  UL muting may arbitrarily determine whether to rest UL transmission in symbols. It is supported to mute 0, 1, or 2 UL symbols within a slot, and the position of these mute symbols may be configured semi-permanently.

IV. Future Directions

While this survey reports 3GPP studies and decisions taken, validating SBFD in the field remains essential. We therefore recommend:
(i) Evaluation of fully dynamic SBFD, including fast sub-band hopping under mobility and beam management.
(ii) Cluster-level UL muting with scheduler integration, quantifying fairness trade-offs.
(iii) UE/device complextiy, power, and thermal characterization.

V. Conclusion

This survey showed how Sub-band Full Duplex (SBFD) evolved from an idea in 3GPP Release 18 to a ready-for-deployment feature in Release 19. It summarized the key Release 18 findings that proved SBFD can boost downlink speed without hurting uplink, and we outlined the Release 19 additions; clearer transmit/receive rules, an SBFD-aware random-access procedure, and new tools for measuring and easing cross-link interference. These steps make SBFD practical while staying compatible with existing 5G devices, and they point the way toward future work on fully dynamic operation and wider-band testing.

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