Final Report: ProSe

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1. Overview

This document provides high level use cases and analysis for public safety direct communication performance. NPSTC and other public safety focused organizations have developed requirements for public safety communications. These requirements capture the capabilities of legacy public safety communication systems while adding new requirements that anticipate the adoption of new services that enhance safety for both the first responder and the public at large.

Globally most public safety organization have either adopted LTE as their next generation public safety wireless system or have begun implementing it. In support of this widespread adoption, 3GPP has responded by developing standards that support the needs of first responders. These include: higher power device specifications, group communication capabilities, priority & pre-emption, mission critical applications, and direct communications.

Synergy between commercial interests and public safety interests have accelerated the adoption of some first responder capabilities while other capabilities with less commercial interest have seen slower adoption into devices. By example, LTE-direct communication standardized by 3GPP as Proximity Services (ProSe) has seen limited deployment into devices. In part, this slow adoption results from ProSe off network mode that is only supported for public safety use and is therefore applicable to a smaller market.

3GPP standards bodies has taken input from public safety organizations, public safety officials, public safety manufacturers, and the cellular industry to develop a direct communications capability, called Proximity Services (ProSe), that is designed to address the direct communication needs of first responders. However, these efforts have not captured all expectations of public safety users and their organizations for direct communications. These shortcomings persist, because to date, ProSe has not been realistically tested or fielded in part due to a lack of UE chip sets that enable form factor trial devices.

Beginning with 3GPP Release 14, 3GPP shifted its focus away from ProSe toward Vehicle to Everything (V2X). V2X communications is designed to provide ubiquitous communication for vehicles by providing communications with networks, with road side digital kiosks providing for example road conditions, and direct communications between vehicles and to pedestrians. This capability is an important part of Smart Car capabilities and has captured the interest of 3GPP standards committees with its huge potential for implementation in all vehicles, infrastructure, and cellphones. As such PC5 the interface between directly communicating nodes in ProSe and V2X has continued to evolve based on V2X requirements. Significant work in V2X has focused on lowering communication latency and improving performance in congested environments. These improvements are directly applicable to some public safety uses cases but V2X vehicle use cases miss some important public safety requirements.

A cardinal requirement of public safety communications is to provide a direct communication capability that does not require any infrastructure and allows first responders to communicate effectively. Direct communications are essential when infrastructure-based communication is not available or when policy dictates that direct communication should be used. Given the slow commercialization of ProSe and the rapid development of V2X both as a standard and in field trials, the future of public safety direct communications could come either directly from ProSe standards or be based on V2X standards. Basing direct communications on V2X leverages a mainstream market where public safety use of V2X is a vertical application. Therefore, the important question then becomes initially for standards development and beyond, what additional requirements that may not exist for the mainstream V2X market are needed to support first responders.

The use cases and recommended requirements developed in this document attempt to capture perceived shortcomings of both ProSe and V2X standards by creating quantifiable requirements that may be addressed as extensions to ProSe, V2X, or by specific configurations that are fully standards compliant. This document is designed as an extension to the requirements already addressed by 3GPP TS22.280 “Mission Critical Services Common Requirements” and TS22.179 “Mission Critical Push to Talk over LTE.” These requirements may also apply to TS22.181 “Mission Critical Video services over LTE” and TS22.182 “Mission Critical Data services over LTE,” however the current scope focuses on voice communications.

2. Acronyms and Definitions

2.1 Definitions

- **Mode** – Operation of equipment in a defined high-level configuration that is constituted by a group of functional capabilities. Functional capabilities may appear in more than one mode, but modes are mutually exclusive. Thus, only one may be selected at a time and they cannot be combined.
- **Hot Spot:** A device providing a Wi-Fi™ AP that typically uses cellular transport for wide area networking access.
- **Flexible Hot Spot:** A Hot Spot that expands the local network access to include other communication interfaces both wired and wireless. E.g: Bluetooth, Ethernet, USB, 7 etc.
- **Hybrid Communication Talkgroup** – A talkgroup whose domain spans network and direct communication links.

2.2 Acronyms

- Ethernet
- FHS Flexible Hot Spot
- HS Hot Spot
- HCT Hybrid Communication talkgroup
- IC Incident Command
- MODEM
- NPSBN National Public Safety Broadband Network
- OAP Opportunistic Access Point
- USB Universal Serial Bus
- Wi-Fi™ Industry alliance for 802.11 products

2.3 References

The following documents contain provisions which, through reference in this text, constitute provisions of the present document.

- References are either specific (identified by date of publication, edition number, version number, etc.) or non-specific.
- For a specific reference, subsequent revisions do not apply.
- For a non-specific reference, the latest version applies. In the case of a reference to a 3GPP document (including a GSM document), a non-specific reference implicitly refers to the latest version of that document *in the same Release as the present document*.

[1] R1-133186: "Typical Public Safety Use Cases, Performance Values, and E-UTRAN Characteristics for D2D ProSe Group Communication", U.S. Department of Commerce

[2] NPSTG Communications Report "Public Safety Broadband Push-to-Talk over Long Term Evolution Requirements", 7/18/2013.

3. Public Safety Direct Communications Range

The ability to directly communicate between user devices without intervening infrastructure has been recognized and accepted as a core requirement for public safety communications. However, the requirements to date have not quantified requirements for communication range. The use cases that follow provide a basis for range requirements. These requirements are based on legacy public safety communications and on new services that are enabled by ProSe.

While the NPSBN is the primary, reliable transport of public safety voice and data, there are many situations where voice and data communications will be required in areas where the NPSBN service is not available either for initial response or for continuing operations.

- *NPSBN Users (NPSBN-U) may be outside of the range of the fixed network, such as first responders in a rural area assisting in a response to a plane crash or police officers inside a residence responding to a domestic issue. Off-network voice communications must be immediately accessible to users in the absence of the NPSBN. This need includes areas and locations where the ability to access non-terrestrial communications can be impaired such as within buildings and other enclosed areas where non-terrestrial communications may not be available.*
- *Additionally, there may be times when users may wish to communicate off-network. Today, firefighters often join a local communications network, which does not leverage the fixed network, but rather, relies on either direct communication between the user devices or communications via a local repeater on-scene. Firefighters can voluntarily leave the fixed network either due to the unpredictable coverage of the fixed network, or if the coverage of direct communications or the local repeater is well known, based on experience.*
- *A user within network coverage needs to communicate with users who are on the network and those that are off-network. By example an Incident Commander (IC) may be located within network coverage while some personnel responding to the fire may have more limited coverage. These users must be able to communicate to users on the fixed network, such as dispatch, as well as the local users who are off-network or when it is desirable to provide voice, data and video connections between users without connection to the network even if within network coverage. Note: – This description addresses current use where first responders must decide whether operations will be on or off network and then command their radios to operate either on network or through direct communications. However, future broadband communications should include that ability to automate this process allowing first responders to communicate with both on network and off network devices as possible by coverage.*
- *A relay function is critical for off-network communications when NPSBN coverage is not enough to support the public safety mission. In the case of firefighters who are responding to a wildfire while outside of the coverage of the fixed network, if one user becomes encircled by the wildfire and is beyond the range of the IC, but within the range of another device that can act as a relay, the endangered firefighter can still update his status to the IC. A UE device operating on the NPSBN should be capable of relaying PTT traffic between a UE device operating off the network and a UE Device operating on the network.[2]*

ProSe provides both communication and discovery capabilities. Communication provides service information conveyance between devices, while discovery is designed to enable devices to find other direct devices operating in proximity. The focus of these use cases is on communication; discovery is treated as secondary. In many cases devices may be pre-configured to communicate for logistical, security, and latency reasons thereby minimizing the need for discovery.

The following use cases are designed to reveal perceived weaknesses in legacy direct (LMR) and ProSe communications with a goal of addressing first responder expectations through these requirements. An attempt has been made to group use cases that have similar technical requirements.

3.1 Use Cases: Direct Communication Range (Noise Limited)

Direct communication noise limited range use cases are characterized by the communication range being limited by the noise floor of the receiver rather than interference in the operating environment. Typical environments providing low noise floors include:

- Areas out of network coverage that may be rural or have geographic RF blocking whether natural or manmade
- In-building coverage where RF losses are high even over potentially short distances and interference is typically low for PS bands
- For direct communications, a low loading of competing ProSe communication links in range

A noise limited use case is specifically provided to capture performance requirement for uncompromised coverage. The noise limited case that follows in the next section captures expectations for performance where interference from network operations, interference from other direct communication active links, or external interference may affect operations.

3.1.1 Mission Critical Voice Range (Noise Limited)

This use case captures the legacy public safety requirement for direct communications.

3.1.1.1 Description: Voice Communications (legacy)

A first responder outside of infrastructure coverage needs to communicate with other first responders in the area using voice PTT to coordinate activities and provide aid as needed. No interstitial communication nodes are available to provide communication relaying. The inability to support voice communication is a serious safety issue.

- Wildfire fighting is performed over large, frequently rural areas with rugged terrain. Workers need reliable communications to coordinate efforts and to provide emergency response when needed. Communication traffic has a low duty cycle and consequently voice communications rarely collide. Legacy LMR technology such as P25 can fail to provide successful communications for remotely located workers, particularly due to natural terrain blockages or large propagation distances. Remote workers are aware that communications may be enabled or improved by moving to local high ground and may do so to enable critical communications as depicted in Figure 1. Fire fighters[1] expect a technology that communicates on par with their existing technology experience with P25. Two requirements follow from this example: communication

[1] As well as other first responders.

range should be at least comparable with P25 and the communication system should allow users to communicate over longer distances by operating from physically advantaged locations.

- SWAT teams operate in high intensity situations where real-time coordination is crucial to the mission. Network communication may be compromised by RF losses in penetrating buildings or other barriers. Generally, the reliability of network coverage in the operational zone is unknown. Direct communication can provide more reliable communications for the SWAT team member by greatly reducing the range and barriers that must be traversed by RF signals. The team would anticipate communication with a next generation technology would match or exceed the legacy capability.
- Search and rescue operations benefit from reliable communications that may require direct communications to provide coverage to remote searchers.
- Firefighting inside buildings is similar to SWAT team expectations for communications.
- 3GPP standards limited an explicit range requirement to the following: [22.280-C20 PR.73*] It is desirable that an authorized public safety UE in or out of E-UTRAN coverage supports the capability to exchange data via ProSe from within a building to public safety UEs outside the building using a power class 3 E-UTRA UE [9].*[2] *From a public safety perspective the requirement would simply exist. The need exists without consideration for the power class.*
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{! REQUIREMENT – Comparable or better communications range than P25

{! REQUIREMENT – Communication range should be extensible by the radio operator to large distances based on an advantaged position (line-of sight communications).

[2] This is the only explicit range requirement in the ProSe study document. Clearly this requirement only captures a single narrow scenario. In addition, it does not define a testable criterion because a building could produce RF losses to great for practical communications, while a small residential building could be nearly loss free.

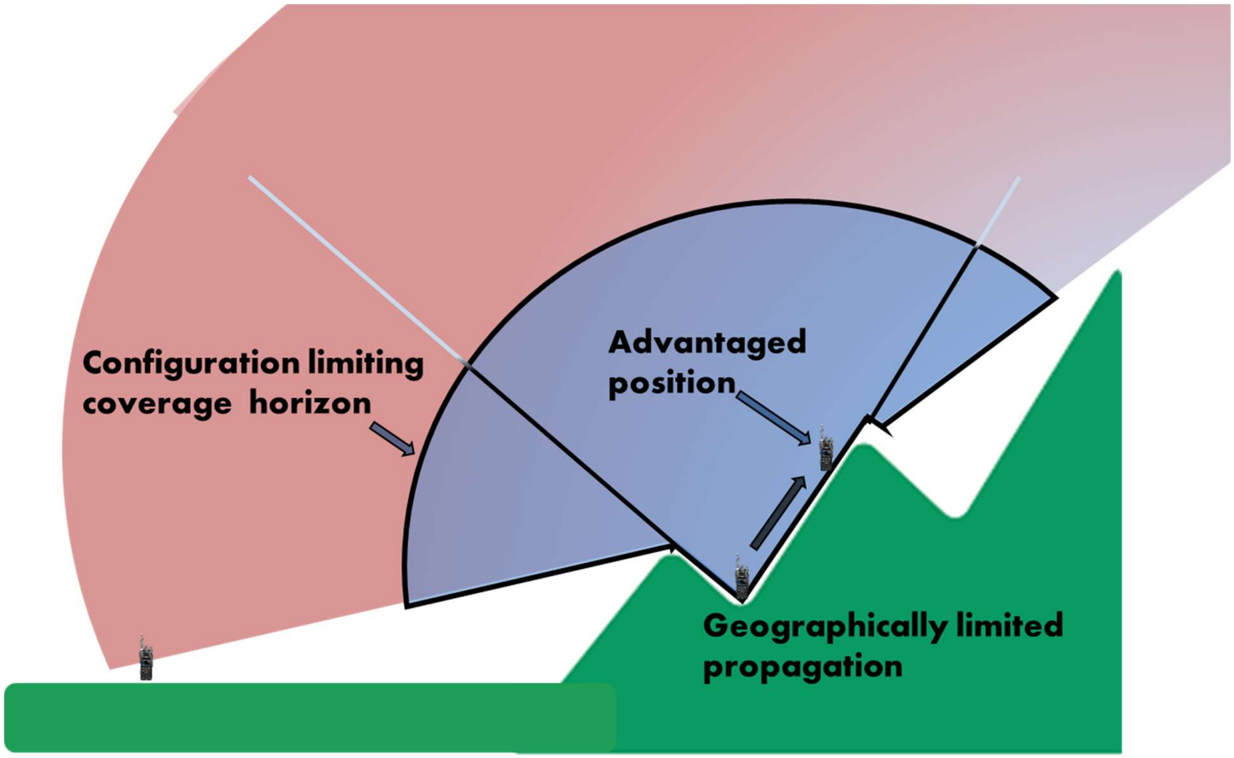

Figure 1, Improved Coverage with Advantaged Position

3.1.1.2 Description: Voice Communications (new)

In legacy communication systems (P25), talkgroups are generally either network based or in the case of P25 direct mode essentially mapped to a physical RF channel. Some proprietary solutions exist for vehicle-based repeaters that may extend the reach of talkgroups. Operation of these systems usually requires intervention by users to enable relay operations, however users are generally not privy to the information required to make an informed decision about which nodes at a scene should become relays or whether relay operation is even required. Therefore, activation of these "repeaters" tends to be based on policy rather than a substantiated physical need to achieve reliable communications. A next generation system should automatically evaluate whether relay operation is appropriate and either autonomously invoke proper relay operations or prompt an appropriate user for approval. This behavior is particularly important in broadband communication where the channel is re-used by each base station and several co-located active base stations/ relays would reduce capacity and reliability rather than enhance it.

{! REQUIREMENT – Coverage extension capabilities including relays should be capable of automatic activation and deactivation based on an assessment of the RF environment and agency policy.

3.1.1.3 Description: Voice Messaging (new)

A first responder outside of infrastructure coverage needs to communicate with other first responders. Direct voice communications are breaking up. The user sends a voice message that can be delivered under these conditions. (Essentially rather than requiring immediate access and continuity of a link between sender and receiver; messaging buffers, reassembles, and delivers the voice message once it can be presented. The first responder may also receive responses using the same mechanism.

Voice messaging may also be applied at the application level. In this instance, multiple communications arrive concurrently at a device. Priority and latency rules for all communications cannot be achieved due to concurrent presentation limitations.[3] The higher priority message is presented, while the lower priority messages if configured for voice messaging are presented later.

{! REQUIREMENT – A public safety direct communication system should include the capability to support voice messaging for poor signal conditions where real-time voice is not possible.

{! REQUIREMENT – A public safety direct communication system whose devices can receive more than one message coincidently should support voice messaging that allows a lower priority messages to be presented once a higher priority message thread is complete.

3.1.1.4 Description: Emergency Messaging (new)

A first responder outside of infrastructure coverage presses the emergency button on a device, because this message is especially critical for delivery the application may take special action when the transport service is not able to establish a voice connection. Typically, in response to an emergency button selection, three different types of information are transmitted:

- A potentially single bit message declaring the emergency: 1 bit
- A presence message providing various vital information about the initiator: hundreds of bits
    - Location
    - Identifier
    - Status
    - Bio-metrics
- An open voice channel: a 15kbit/sec. transport with continuity, priority, and preemption.

Each of these sessions varies widely in its transport throughput and service quality requirement. The application may request configurations of the transport that maximize delivery of the emergency declaration and presence when more demanding services cannot be supported.

{! REQUIREMENT -The communication service should provide mechanisms to prioritize service delivery of emergency declaration and presence messages when an open voice channel may not be supportable.

3.1.1.5 Applicability: Noise Limited Range

Applicability: search and rescue, fugitive search, wild fire fighting, remote patrol, in-building communications, SWAT operations, firefighting, et al

3.1.1.6 Trigger

Pressing the PTT or emergency button.

[3] The most obvious example would be a limitation of one voice presentation at a time by a device.

3.1.1.7 Primary Actor

A first responder is using PTT or the emergency button to communicate and expects to hear a voice acknowledgement upon successful communications.

3.1.1.8 Supporting Actors

The receiving first responder upon receiving an intelligible message will respond to the initiator.

3.1.1.9 Stakeholders

First responders

Manager of first responders

System managers

3.1.1.10 Issues

There is no obvious limit to the range over which the radio operater might desire communications. However, a minimum standard can be set by legacy technology. First responders are aware of the limitations of their current technology and could anticipate that a new technology would at least meet current capabilities. This requirement is also consistent with NPSBN recommendations provided in Table 9, row 3 and 4.

3.1.1.11 Derived Requirements

{!REQUIREMENT – The next generation direct communication solution should match or extend the maximum RF link losses (range) that support voice with a DAQ of 3.4.[4]

{!REQUIREMENT – The next generation direct communication solutions should provide a network bridging relay that extends communication services to off network UE by relaying traffic from its network link to its direct link.

{!REQUIREMENT – The next generation direct communication solutions should provide a direct coverage extension relay that extends the effective coverage range of direct communication links via an intermediate relaying node.

{!REQUIREMENT - [22.803-c20 PR.65] An authorized public safety UE may be capable of acting as a relay in or out of E-UTRAN coverage for other public safety UEs.

{!REQUIREMENT - [22.803-c20 PR.66] An authorized public safety UE shall be capable of being enabled/disabled by a user or system in or out of E-UTRAN coverage to act as a relay for other public safety UEs.

{!REQUIREMENT - [22.803-c20 PR.67] The user of a ProSe-enabled public safety UE acting as a relay should not perceive service degradation due to its use as a relay in or out of E-UTRAN coverage.

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[4] 3GPP has extensively evaluated voice quality for public safety using MOS (mean opinion score) in 3x.yyy. For these evaluations, it uses a MOS score for its recommended mandatory CODEC AMBR-W at xxyy bps. In certain conditions talkgroups may use the P25 voice codec.

{!REQUIREMENT – The next generation direct communication solution should support a mechanism to increase link margin for delivery as a non-real-time service like voice messaging, emergency declarations, presence, and texting.[5]

3.2 Use Cases: Direct Communication Range (Interference Limited)

Direct communication interference limited range use cases are characterized by the communication range being limited by interference that exceeds the receiver noise floor. Typical environments with these interference conditions include:

- Areas within network coverage, where network traffic generates interference for direct communications.
- ProSe generated self-interference. Direct communication links in range may compete for the same RF resources (resource blocks) generating significant mutual interference. Similarly, direct communication links using disjoint RF resources but in the same band generate harmful interference due to limited inter-resource block isolation[6]. A typical ProSe transmitter while using a small number of available resource blocks for its transmission will also elevate the noise floor across the entire allocated bandwidth for a nearby receiver. Thereby limiting its ability to receive a concurrent message from a transmitter further away using different resource blocks. A second limiting mechanism is the receiver's ability to reject in-band energy from a nearby transmitter using separate resource blocks. In this case the transmission power from the nearby transmitter's selected resource blocks captures the AGC of the receiver. A weaker signal in a different part of the band is suppressed and may not be decodable.
- External interference generated by signals outside the operational band or if within the band then external to the intended licensee of the band.

3.2.1 Description: Voice Communications (legacy)

A first responder outside of infrastructure coverage needs to communicate with other first responders in the area using voice PTT to coordinate activities and provide aid as needed. In this case the first responder is part of a multi-jurisdictional and multi-agency response to an emergency. Voice communication is organized into groups that may include: locally assigned personnel, mutual aid personnel, and command personnel. Additional voice groups are needed for the incident response. The large number of communicators and the segregation of these users into groups places a burden on the available RF resources. Communications may encounter interference associated with the inability to provide completely independent radio resources for each active talk group. Next generation communication systems should provide the same or better capacity, range, and call blocking performance.

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[5] This requirement is meant to ensure that crucial messages can be transferred successfully even with poor link conditions. Solutions could include application level persistent transmissions until acknowledgement or lower level protocol enhancements.

[6] The limited isolation is a function of RF performance and protocol design.

Each agency and jurisdiction can be expected to have its own communication groups as well as other groups for coordination. As part of incident management some groups might be combined, while others may be formed for coordination. Relays are excluded from this use case.

{!REQUIREMENT – The next generation direct communication solution should match or extend the capacity, range, and call blocking performance in congested environments of previous technology for example P25.}

3.2.1.1 Description

A first responder that uses legacy (LMR) direct communications is provided with a ProSe capable device to evaluate during field exercises. Naturally comparisons are made between the observed capabilities.

3.2.1.2 Level

This use case is a high-level summary.

3.2.1.3 Trigger

3.2.1.4 Primary Actor

A first responder is evaluating a device with direct communication capabilities that use ProSe.

3.2.1.5 Supporting Actors

Additional first responders are supporting the evaluation by providing a group communication scenario and providing responses to the primary actor communications.

3.2.1.6 Stakeholders

First responders

Manager of first responders

System managers

3.2.2 Issues

3.2.2.1 Scenario: Incident Command Center

A command center is established to address a multi-department, multi-jurisdictional public safety incident. The distribution of UE includes multiple clusters of devices as well as distributed devices. For purposes of study two types of UE clusters are defined: command centers and teams.

Teams share common group communication configurations. By example members of a team share a common talkgroup that is used for primary team communications. Team members may also have additional talkgroups that are secondary and primarily used for voice monitoring. Further, a first responder may switch the primary talkgroup by selection on the device. The monitored talkgroups are considered secondary in the sense that the principal talkgroup is preemptive for both inbound and outbound communications. While ProSe transport can deliver multiple simultaneously active talkgroups to a single device, the best way to present multiple overlapping conversations is an open area of study. For purposes of this work, principal talkgroups are delivered with priority and preemption, secondary talkgroups are delivered on a best effort basis.

A command center (CC) UE cluster is characterized by a group of public safety command leaders that are coordinating between incident teams. Coordination is typically facilitated by physical proximity to other incident leaders but may also include remote communication particularly up a chain of command. These remote communications may share a common resource or use other communication resources. For purposes of this discussion communications with parties separated from the incident are considered to have a minimal effect on incident communications.

Therefore, a principal concern is the significant harmful interference that may result from a command center cluster of UE operating in direct mode where members of the CC cluster would typically communicate on dissimilar talk groups to their teams. In this scenario, UE transmissions from the CC cluster are all nearby and create interference for any members of the cluster that need to receive while any other device is transmitting the vicinity.

A secondary concern would be similar interference with Team clusters. However, Teams are generally expected to have less interference due to their use of a common talkgroup. Furthermore, with audio communications the group would naturally coordinate their voice. Local transmissions within the Team cluster would be easily processed by other team member devices.

Finally, the use case where a single UE using a different principal talkgroup enters the vicinity of a team cluster which share the same principal talkgroup. However, this case is just a limiting case of the command center scenario. In the command center case devices are clustered and some number of these devices may transmit on different talk groups. The team cluster with one device on a different talkgroup is just the case of one potential transmitter of a dissimilar talkgroup.

The command center and team cluster locus may include a mix of in network coverage and out of network coverage with the following environments possible.

1. Both the command center and incident are completely outside network coverage. Direct communications are used for all communications.
2. The command center is in coverage, but incident teams are primarily outside coverage.
3. The command center is out of coverage, but the incident teams are in coverage. Since network communications are more efficient and more capable, best practices would suggest that this configuration should be avoided. Generally, the command center should be located such that it has network connectivity.
4. Both the command center and incident are completely inside network coverage and no LTE-direct communications are used.

3.2.2.1.1 Interference Mechanisms

A transmitting LTE-direct device may interfere with other receiving devices in the following circumstances:

1. The LTE-direct device transmits during a network connected device transmission and blocks the serving eNB from receiving the packet.
    a. This case can be avoided by using hybrid communication groups. Specifically, any device close enough to a base station to cause interference should establish a network connection. The network connection control channel will then manage this interference. LTE-direct only talkgroups should not be used in network coverage.

   b. It is also presumed that operation on LTE-direct and network in the same band with proximity involve the same spectrum owner.
   c. Adjacent band interference is also possible – In this case the interfering LTE-direct device is strong enough to affect the eNB from an adjacent band.
2. The LTE-direct device transmits while another LTE-direct is attempting to receive a different LTE-direct. Reception is blocked.

{! CONFIGURATION – LTE-direct only talkgroups should only be used outside of network coverage. Note while LTE-direct devices might use network resource scheduling while operating exclusively on an off network talkgroup and thereby avoid some interference, a significant amount of interference may also be generated by the shared use of the channel even with disjoint resource block allocations. LTE-direct even when using network scheduling is not able to manage its transmission power as effectively as a unicast uplink message that is power backed off by the serving eNB. Group based LTE-direct signals small generally operate at full power to effectively reach all members of a group.

{! REQUIREMENT – A device within network coverage should establish synchronization with the local eNB even if its communications are exclusively direct.

{! REQUIREMENT – A device with network connectivity should use the network connection for its communications when the required service is available.

{! REQUIREMENT – When a service is not available, a device should consider based on policy, configuration, and RF metrics whether to become a network bridging relay.

3.2.2.2 Environment 1a: Initial Incident Response: Network Coverage
Responder perspective - Following notification of an incident, public safety officials begin responding. Typically, a police officer may be first to arrive. Following a quick initial assessment, the officer reports back to dispatch initial requirements for further response. While waiting for back-up the officer may step away from his vehicle to begin initial incident response. Having further appraised the incident the officer communicates with dispatch to request additional support requirements. Incidentally, the officer may notice a difference in channel grant tone or display notifications because his connection is using an LTE-direct relay to provide service.

Behind the Scenes: The dispatch vehicle includes LMR and LTE equipment that provide greater reach (coverage) than portable devices. Proximity to the responding vehicle maximizes the officer's ability to connect with dispatch directly. The vehicle equipment in conjunction with the officer's portable device will automatically configure communications to maximize communication efficiency while maintaining coverage. Optionally the officer may choose to override automatic selection of a communication path, but generally the officer would not have the information to make a better decision than the system.

Either due to natural or manmade geographic morphology or building penetration losses the officer's portable radio loses coverage to serving networks as he steps away from his vehicle and into the incident. Prior to coverage loss and without user intervention, the officer's radio initiates a request for relayed service using LTE-direct. The service is initiated and provides seamless service for the officer. [Relay – single client; low loading]

{! REQUIREMENT – ProSe enabled devices should be configurable to automatically initiate methods to maintain connectivity as network communications become less reliable including direct communication links.

{! REQUIREMENT – ProSe enable devices should be configurable to automatically initiate LTE-direct connectivity based on policy, events, and RF metrics. For example: ProSe may be enabled whenever an officer leaves a vehicle.

{! REQUIREMENT – LTE-direct capable devices should be configurable to automatically return to network communications according to policy, events, and RF metrics.

{! REQUIREMENT – LTE-direct enabled devices may be configured to automatically request via direct communications a connection to the macro network whenever it loses reliable network connectivity. Another LTE-direct device may respond by providing a network bridging relay.

{! REQUIREMENT – When it has network coverage, a LTE-direct device configured to provide network bridging relay service shall respond to a requesting ProSe device with relay service after exchanging appropriate credentials that may include: security, priority and jurisdiction.

3.2.2.3 Environment 2a: Back-up Arrives

Responder perspective - Additional responders arrive at the incident. First responders are aware that communication groups (talkgroups) may be configured for network only, LTE-direct only, or to bridge both networks. In addition, first responders may recognize that their communication device display indicates, and audio annunciations provide status about the current scope of a communication group. Users may occasionally, be notified by the system or become aware through direct observation of communication responses that they may not be able to reach all members of a talkgroup.

Behind the scenes – The communication system is tasked with maintaining reliable communications for first responders. Devices that may use LTE-direct present information or accept inputs for transmission in accordance with a hierarchy. From a reception perspective:

- A signal must be present at the device antenna with enough quality that it can be processed by the device. For purpose of this discussion this is defined as RF coverage. The quality metric includes SINR and other signal attributes that may affect receiver processing. For instance, multipath with sufficiently long delay paths could preclude reception.
- An LTE-direct device may fail to capture transport blocks even in RF coverage because its receiver does not capture signals on the target channel. For devices using network services, lost data due to radio availability is unusual. Devices transmit and receive simultaneously. Non-delay critical data is cached by the network or device and sent when the device is active on the required band. Delay critical data may fail because it cannot be sent in compliance with its delay constraint. Some data may be delivered late as appropriate for the application. Devices operating on network may be designed to minimize these types of outages using a combination of proper radio management and by using more than one receiver in the device. Proper design ensures that missed transport blocks are unusual for network operation. However, devices operating in LTE-direct mode are more subject to missed messages because the radio operates in time division duplex (TDD.) Neither the local network nor other communication devices are directly aware of the transmit or receive status of a device that is operating in LTE-direct due to

distributed scheduling. By example, a transmitting ProSe device is blind to other ProSe transmissions in the same band and in general will not receive them and does not know that transmissions have occurred. To ensure proper prioritization of calls LTE-direct should implement a mechanism for a transmitting device to detect that another device is active and take appropriate preemption and prioritization actions. This action might include skipping transmission in some PSCCH periods to listen for higher priority transmitters.

- The ProSe control message includes prioritization within its control message format. Therefore, a device may compare its transmission priorities with received message priorities to determine proper handling of messages that require arbitration. Likewise, V2X includes message priority.
- Finally, a device application makes a final determination about service priorities and releasing TX data for transmission. By voice example, a device might receive simultaneously a telephone call, more than one network talkgroup, more than one talkgroup from a ProSe source, while the device operator also wishes to originate voice traffic. The device must make clear to the operator what services are being prioritized, while providing mechanisms to the operator for override. The emergency button would be an example of user override.

{REQUIREMENT! – LTE-direct group communications should support self-preemption of an active transmission if another device begins transmitting using a higher priority on the same talkgroup.

{REQUIREMENT! – LTE-direct multicast communications should support self-preemption of an active transmitter based on a combination of priority and congestion metrics.

{REQUIREMENT! – LTE-direct unicast communications should support self-preemption of an active transmitter based on a combination of priority and congestion metrics.

{REQUIREMENT! – LTE-direct reception should support configurable arbitration between its reception and transmission functions based on priority and policy.

{REQUIREMENT! – LTE-direct devices should also support configurable arbitration between multiple services that may include multiple transport domains.

3.2.2.4 Environment 3a: Incident Command

Responder Perspective - Following an initial adhoc response, an incident command is set-up to coordinate between response groups, to enable senior command to manage the incident response, and to provide communications to political officials. From a communications perspective, two phases may exist for incident command. Initially team leaders may begin coordinating on preplanned talkgroups. As the incident response develops at least some team leads congregate to a physical command center that is in proximity to the incident.

Behind the scenes –During the initial phases of response to an incident, communication is primarily a function of the capabilities of existing network coverage with an overlay of direct communication capable devices brought with the responders. For smaller incidents, local enhancement to this intrinsic communications capability may not be warranted. For larger incidents requiring an extended response additional equipment can be brought to the scene to enhance communication capabilities. The role of direct communication services may evolve over the course of an incident response[7], but the communication system should be designed to provide uniform and predictable service capability for first responders.

For an incident where network coverage is widespread, but not ubiquitous direct communications provides a vital role in extending services into coverage gaps. As responders advance deeper into an incident their communications may seamlessly transfer to direct communications as network coverage limitations occur. This transfer to LTE-direct is enabled by devices either detecting LTE-direct activity or switching to it to maintain connectivity. Switching conditions are a function of configuration, public safety policy[8], and RF metrics.

Similarly, the network connection behavior is a function of connection logic, carrier policy, public safety policy, and RF metrics. Subject to device limitations, multiple simultaneous connections are presumed.

To keep first responders' focus on the incident and not on their communication devices, the communication application and airlink transport automatically provides pruning (arbitration) as necessary between multiple data sources. In simplest form, the highest priority is presented, however depending upon the data type multiple sources may be presented concurrently. For example: audio communications and a presence map update may be coincidently updated.

For both network and LTE-direct the communication systems need to manage congestion, priority, and preemption.

3.2.2.5 Environment 1b: No Network Coverage

This section focuses on differences between partial network coverage and no network coverage at the incident. Following notification of an incident public safety officials begin responding to an incident. Typically, a police officer may be first to arrive. Following a quick initial assessment, the officer finds that communication with dispatch is not possible. While waiting for additional back-up the officer may step away from his vehicle to begin initial incident response. The officer's portable radio and vehicle radios establish a ProSe connection.

3.2.2.6 Environment 2a: Back-up Arrives

As back-up arrives the officer is automatically alerted to arriving support as arriving devices communicate presence information and arriving personnel communicate verbally. Communication as a result is a combination of direct communication and relays that are automatically initiated based on conditions. Back-up personnel establish communication back to dispatch and provide assessment and support requirements.

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[7] An implicit presumption is that network connections will provide more services and better capacity than LTE-direct. Therefore, incident response is expected to enhance local network performance and coverage whenever the scale of the incident is sufficient to warrant such actions. Therefore, LTE-direct is expected to play an important role in: initial response, smaller incidents, and in isolated environments like buildings.

[8] Public safety policy in this context may include some integration of local, jurisdictional, organizational, and national components.

Behind the scenes – Communication support at the scene has more limited capacity than what is generally available from network coverage. The LTE-direct service must provide congestion management functions to ensure that communications are properly prioritized.

3.2.2.7 Network Relays

As back-up arrives to an incident that may benefit from relaying functions that extend network coverage, the system should automatically utilize the aggregate relaying capabilities effectively. Legacy LMR vehicle repeaters (relays) must be carefully managed to prevent harmful self-interference. Next generation systems should self-manage interference issues.

Legacy LMR vehicle repeaters may operate by either generating a cross band bridge between frequency separated LMR bands or by time division multiplexing a single band. In both cases, vehicle repeaters are generally enabled by the vehicle operator when their application is expected to be helpful. Two problems that may arise include: a first responder leaving a vehicle without anticipating and enabling the repeater. The first responder subsequently loses coverage while away from the vehicle. Second, multiple repeaters may become active at a scene and generate harmful interference to relaying operations. Depending upon the affiliation of various potential vehicle repeaters at an incident, configurations may include a common operating channel or frequency spaced close enough to generate significant interference. Consequently, only a small number of repeaters that are carefully planned can operate in proximity. At larger incidents, distances required for interference free operation can be complicated and certainly difficult for personnel to manage in the field.

Next Generation Behaviors – A next generation relay capability should not only match the current capabilities of existing vehicle repeaters but should also address shortcomings:

- Automatic relay initiation based on need
- Initialization by local (in-vehicle) or remote personnel via a portable device
- Management and mitigation of harmful interference
    - Between network and direct networks
    - Between relays
- Enhancement of relay coverage based on activation of multiple relays

{REQUIREMENT! – An LTE-direct device that is configured to support relay operations should support automatic initiation. The device may base relay need on its own evaluation of the local RF environment.

{REQUIREMENT! – An LTE-direct device that receives an explicit command either locally or remotely should initiate relay operation.

{REQUIREMENT! – LTE-direct devices acting as relays should automatically assess their operating environment and take actions to minimize and mitigate harmful interference.

{REQUIREMENT! – LTE-direct devices acting as relays should coordinate with other proximate relays to ensure that each relay is accretive to overall capacity and coverage while considering priority, preemption, and jurisdiction.

3.3 Conclusions

A next generation communications capability should provide as a minimum standard the same level of range, reliability, and predictability as its predecessor. Wherever possible it should provide improved performance, convenience, services, and coverage.

4. LTE-direct Description

LTE-direct is used throughout this document to refer to LTE communication capabilities that include direct communication or direct discovery of proximate devices via communication paths directly between devices. The term may refer to any of the following:

- ProSe (Proximity Services) or D2D (Device to Device) communications – These terms are largely used synonymously within the 3GPP standards with RAN (Radio Access Network) documents primarily using D2D while other documents use ProSe.
- V2X (Vehicle to everything) – Communications here may refer to V2V (Vehicle to Vehicle), V2I Vehicle to Infrastructure[9], and V2P (Vehicle to Pedestrian)
- The 3GPP based evolution of direct communication included in 5G standards
- Communications capabilities that may be extensions to 3GPP standards

Infrastructure may provide significant support to LTE-direct operations depending upon the operating scenario including:

- Setting of operational parameters prior to LTE-direct operations
- Provisioning of RF resource allocations for LTE-direct operations
- Real time scheduling of LTE-direct resources for each transmitting UE
- Real time modification of RF allocations or operational parameters

LTE-direct may also operate independently and without any support of infrastructure as either a temporary or permanent operational mode. D2D public safety modes and some V2X modes support fully autonomous LTE-direct operations.

4.1 Standards

Primary standards for LTE-direct are developed by 3GPP. Beginning in Release 12 with a study and subsequent normative work ProSe basic capabilities were defined. Release 13 continued this work and completed additional features. Following Release 13 the focus of 3GPP has been V2X which uses the same underlying physical airlink interface (known as PC5), but includes additional requirements designed for low latency and congestion control. Table 1 illustrates a summary of primary features of ProSe.

Table 1, ProSe Highlighted Features by 3GPP Release

Features	R12	R13	R14	R15
Discovery (EPC based)	B			
Discovery (direct)	B			
Communications (E-UTRAN)	Multicast	Unicast added		
Communications (WLAN)	B			
Communications off network (PS only)	Multicast			
Relay UE to Network (PS only)		E		
Relay UE to UE (PS only)		Not addressed		

[9] Infrastructure that might use LTE-direct could include road side kiosks dispensing construction warnings, road conditions, or advertisements.

4.2 LTE-direct Overview

LTE-direct is intended as an inclusive term to include:

- 3GPP standards
  - Proximity Services that were developed to handle commercial applications for direct communications and public safety specific requirements. In particular the ability to communicate without a network.
  - Vehicle to Everything (V2X) that was developed to support Smart Car communications and rapid communication between vehicles and infrastructure to provide critical awareness of the surrounding environment for road hazards and nearby vehicles. This standard also supports off network communications and has main stream support because of its general applicability to all vehicles.
  - 5G versions of Proximity Services and V2X.
- Profiles
  - Configurations of 3GPP standards that support public safety critical communication use cases.
- Standard extensions
  - Capabilities in direct communications that are not directly covered by 3GPP standards.

4.3 Standards Based ProSe Evolution

ProSe particularly its use in public safety modes represent a very small part of the cellular market. Consequently, ProSe standards have not been quickly implemented. V2X by contrast has a very large potential market and has garnered significant focus within the 3GPP standards. An increasingly likely way forward would be to treat public safety direct communication requirements as a vertical market within a V2X umbrella. In this approach, only those requirements that were unique to public safety would need to be addressed within V2X standards.

4.4 Extensions Beyond the Standards

Potential additional capabilities and performance features that are not included in the 3GPP standards

4.5 Public Safety Profiles

Configuration of ProSe and its extensions to that provide improved performance that are designed to ensure public safety grade reliability.

5. Results

5.1 Performance in Noise Limited Conditions

In interference free areas, communication range is limited by the maximum RF propagation losses that result in a signal at the receiver with enough quality to support a grade of service. Legacy LMR direct communications is primarily used for voice services. A natural comparison may be made between the relative range of LMR direct communications and LTE-direct while each provides voice services meeting a public safety grade.

Legacy direct communications typically use either conventional FM or P25 CAI (Common Air Interface) for direct communications. Table 2 is an excerpt from TSB88.1-D Table A 1 illustrating voice quality measured as DAQ (Delivered Audio Quality) as a function of SINR (signal to interference plus noise ratio.) DAQ-3.4 is generally accepted as the minimum standard for mission critical voice and is defined as: *"speech understandable without repetition. Some noise or distortion present."* As shown conventional FM SINR requirements vary significantly depending upon the channel width allocation and FCC rules associated with its emission mask. P25 is designed to fit in the narrowest channel supported by the FM configurations illustrated. Across all configurations P25 requires a lower SINR to deliver public safety quality voice. The table also provides pre-migration and post migration performance for P25. Post migration relies on a narrow receiver filter to provide better rejection of off channel interference and noise. Post migration is more representative of newer P25 receivers. To simplify comparisons with legacy LMR technologies, P25 post migration with a DAQ-3.4 will be used as a basis for comparison with broadband technologies unless otherwise noted.

Table 2, Voice Quality versus Channel Quality

	DAQ-3.0 (BER%/SINR)	DAQ-3.4 (BER%/SINR)	DAQ-4.0 (BER%/SINR)
Analog FM Radios			
FM +/- 2.5 kHz	23	26	33
FM +/- 4 kHz	19	22	29
FM +/- 5 kHz	17	20	27
P25 Radios			
C4FM (IMBE) (12.5 kHz) pre-migration	2.6/15.2	2.0/16.2	1.0/20.0
C4FM (IMBE) (12.5 kHz) post migration	2.6/16.5	2.0/17.7	1.0/21.2

To form a basis of comparison between LMR and LTE technologies a single approach to testing and modeling is required that equitably addresses fundamental differences in their technologies. LTE was developed to maximize capacity while minimizing cost for commercial service. In contrast, LMR was specifically designed for mission critical services to provide reliable communication, particularly voice. To provide reliable communications, LMR depends upon high performance equipment. It uses high power base stations, high RF power devices, and very selective receivers to maximize reliable communications and avoid interference from other LMR devices. In contrast LTE base stations have much lower power per MHz (spectral density), devices generally radiate about 0.1 W of RF power (includes some antenna losses), and receiver performance is heavily traded against cost models. This study identified areas of measurements differences and attempted to unify a single method to evaluate performance. Specifics areas that differed included:

- Audio quality – P25 audio quality is measured by DAQ, while 3GPP standards use MOS (Mean Opinion Score). Unfortunately, a direct conversion does not exist between DAQ and MOS.
- RF channel modeling – Most performance modeling in LMR is done with a flat fading (Rayleigh) model because the RF channel is narrow and expected to have relatively consistent characteristics across its bandwidth. LMR direct communications distances are generally shorter than network coverage and therefore multipath delay is not anticipated to be significant issue for LMR-D. By contrast, LTE-direct signals may be several MHz wide and

therefore significant frequency selective fading can be anticipated across the LTE-direct channel. Consequently, we have adopted LTE channels models as a single common fading channel model for evaluations.

- Protocol – LMR communications uses a fixed transmission signal, while LTE is adaptive across multiple dimensions. LMR direct communications uses a fixed transmission power, fixed modulation method, and fixed forward error correction code. In contrast, LTE-direct may vary its transmission signal in accordance with network provisioning, device configuration, channel conditions, and estimated RF loading. Transmission power, MCS (Modulation and Coding Schemes), and its use of frequency & time elements may all be varied. To simplify the comparison LTE will be configured to maximize its range. However, it's important to understand that specific instances of LTE-direct may have shorter ranges due system tradeoffs with network performance or a requirement to meet throughput for the application.

5.1.1 Audio Quality

Audio quality in LMR systems and cellular communications are commonly measured with differing methodologies. While LMR frequently use DAQ (Delivered Audio Quality), the cellular industry commonly uses MOS (Mean Opinion Score). No commonly accepted conversions are provided between these two measures. However, DVSI the developer of the P25 voice coder has MOS data for the P25 coder and TSB88 provides DAQ performance as a function of BER and equivalent SINR. Table 2 is an excerpt from TSB88 that provides the expected DAQ as a function of SINR and equivalent SINR. A DAQ 3.4 is generally accepted as mission critical grade audio and requires a BER of 2% or equivalently 17.7 dB SINR.

DVSI the developer of the P25 voice coder has test results for MOS as illustrated in Figure 2. Although this data does not allow direct correlation a comparison can be made with some interpolation of the MOS data. The red bars illustrate the original P25 vocoder performance that was selected for use in P25 communication systems. The green bars show the "half-rate" vocoder that is used in trunking P25 systems. The blue bars illustrate improved performance that DVSI introduced after the standardization of the "full-rate" coder. It is fully compatible with the original P25 vocoder and reflects current P25 system performance.

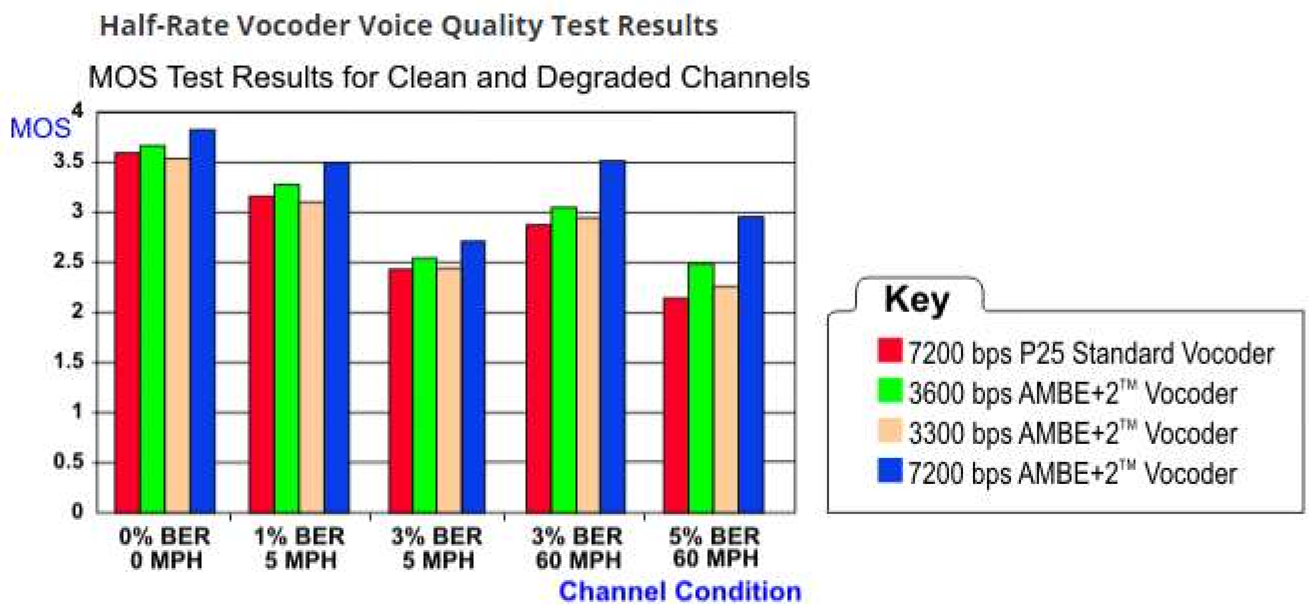

Figure 2, AMBE Vocoder Performance

An estimate of MOS at 2% BER can be made by averaging the second, third, and fourth blue bars which results in a MOS of 3.2 for 2% BER.

5.1.2 RF Channel Modeling

For performance evaluations, 3GPP propagation fading models from 36.101 were used. The 3GPP models include multipath profiles for pedestrians and vehicles as well as geographic morphologies for urban and suburban areas. This model allows direct evaluation of air link protocols under a variety of multipath profiles. Figure 3 illustrates a summary of model profiles.[10]

Model	Number of channel taps	Delay spread (r.m.s.)	Maximum excess tap delay (span)
Extended Pedestrian A (EPA)	7	43 ns	410 ns
Extended Vehicular A model (EVA)	9	357 ns	2510 ns
Extended Typical Urban model (ETU)	9	991 ns	5000 ns

Figure 3, 3GPP RF Channel Models

5.1.3 P25 Performance

As a basis of comparison with LTE-direct the P25 CAI (Common Air Interface) used for direct mode operation was simulated for performance with 3GPP fading models. The models were applied with 5 Hz and 70 Hz doppler using EPA, EVA, and ETU models. The results are illustrated in Figure 4, and are consistent with performance expectations based on TSB-88 and previously illustrated in Table 2. To achieve DAQ-3.4 public safety grade voice a SINR of 17.7 dB providing a 2% BER was required in faded

[10] Detailed model parameters can be found in 36.101 Annex B.2.1.

conditions with a doppler of 5 Hz. The simulation results show that a 2% BER is achieved at 17.7 dB; matching the TSB88 table.

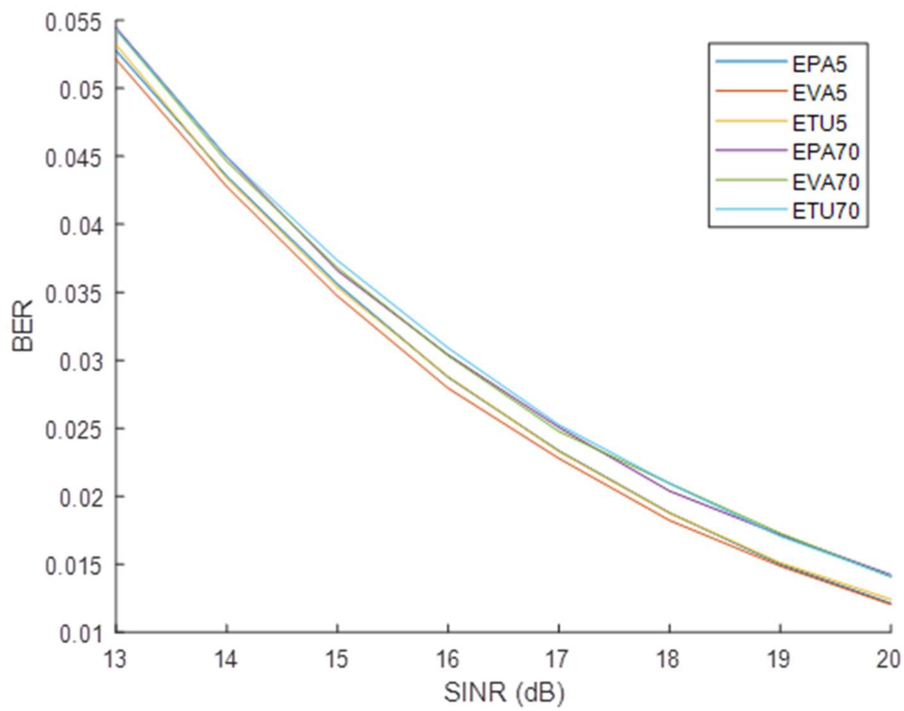

Figure 4, P25 BER Curves- PS Voice for BER < 0.02

A total of six simulations were performed with performance curves clustering into two groups. The upper cluster illustrates the BER performance with a doppler shift of 70 Hz and three multipath profile models. Differences in performance between the multipath profiles are minimal. Similarly, the 5Hz doppler case are also clustered. From these graphs we can conclude that performance differences between the delay profiles in minimal, while the 70 Hz doppler cases lose about 0.5 dB of performance.

Maximum RF losses for acceptable performance is an effective way to measure the performance of a communication transport. For P25 CAI operating in direct mode in the 700/800 MHz band, Table 3 illustrates primary parameters associated with maximum link losses. Public safety grade LMR portable radios from major manufacturers generally provide 3 Watts of RF transmitter power in the 700/800 MHz band. MIMO processing including diversity is not supported. The IF bandwidth and noise figure are typical of public safety grade devices. Faded voice performance is taken from Table 2. From these parameters, the maximum RF coupling loss can be calculated.

P25 direct communication out performs conventional FM by 7.5 dB for a DAQ-3.4.[11] The relative coverage is based on an average propagation exponent of 4.0 that corresponds to higher average losses

[11] This difference results from the P25 digital protocol outperforming conventional FM for a given signal quality and because FM requires a wider IF filter that accepts more noise. Although conventional FM performs poorer at DAQ-3.4 some public safety users continue to use conventional FM for direct mode because in very poor RF conditions it can be possible to communicate with conventional FM, using repeated attempts, because it degrades

for direct communications because path obstructions and losses are higher when antenna heights are low for both sides of the RF link.

Table 3, LMR RF Link Performance

	P25 Portable	Conv FM Portable
Nominal Tx Power	35	35
MIMO	1x1	1x1
Rx Effective IF Bandwidth (kHz)	6	12.6
Rx Noise Figure (dB)	6	6
Faded Performance Threshold DAQ3.4 (dB)	17.7	22.0
Faded Performance Maximum RF Coupling Loss (dB)	146.5	139.0
Antenna Efficiency. (dB)	0	0
Maximum Link Loss	146.5	139.0
Radial Coverage Relative	1.00	0.65
Area Coverage Relative	1.00	0.42

5.1.4 ProSe Performance

Evaluation of ProSe performance is much more complicated than LMR technologies because LTE-direct is an adaptive waveform whose performance changes as a function of its configuration, adaptation to channel conditions, channel loading, and transmitter power.

- Configuration – ProSe provides significant configurability of the Sidelink signal. A significant aspect of this research is to understand configurations suitable for public safety use.
- Adaptive Channel Coding & Allocation – The data transport channel of ProSe is managed by the upper layers of the protocol, that can affect tradeoffs between throughput and receiver sensitivity. Resources are allocated as PRB's (Physical Resource Block) that consist of 0.5 msec. time slices and 180 kHz bandwidth. Generally, PRB's are allocated in pairs in the time domain resulting in a time scheduling granularity of 1 msec. In the frequency domain, up to 50 PRB's may be allocated in a 10 MHz carrier. Within each PRB ~20 different MCS (Modulation and Coding Schemes) may be selected that tradeoff larger transport blocks with higher SINR requirements.
- Spectrum/ Channel Loading – ProSe performance is affected by channel activity in its allocated band and adjacent bands. When operating in off network public safety modes, scheduling of PRB resources is performed independently amongst active transmitters. Each transmitting device employs a Resource Allocation Algorithm (RAA) that attempts to minimize overall system interference. Receivers capture a composite signal of all transmitters, noise, and interference. Like any RF link, signals that are too weak relative to the receiver noise floor cannot be decoded.

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slowly, while P25 tends to have a strong threshold below DAQ-3.0. It is also believed to exhibit fewer artifacts in noisy audio situations.[11]

In addition, ProSe has several mechanisms that introduce interference into the received signal and effect overall performance.

  - Two or more transmitters select and transmit on the same RF resources; commonly called a collision. In this case, successful communications occur only to receivers that capture a signal with significant signal quality to be decoded. Typically, a receiver may not decode any of the transmitted signals or if one signal dominates at the receiver then it may be decoded.
  - A receiver captures multiple signals that all use different RF resources. However, due to a limited receiver dynamic range[12], the receiver is not able to decode weaker signals that are in effect suppressed by stronger ones that may capture the receiver automatic gain control.
  - A receiver captures signals in its allocated carrier bandwidth but is subject to a much stronger adjacent carrier that reduces receiver performance.

- Transmitter Power – As part of minimizing interference between transmissions, ProSe is required to back off its transmission power under certain conditions. These rules make it harder to predict when communications will be successful.

For performance evaluation LTE-direct may be partitioned into four separate signals that can be considered separately and together:

- SLSS/ PSBCH – contains synchronization information and basic parameters of LTE-direct. It is used to share synchronization between ProSe devices. The synchronization signal is the primary mechanism for shared synchronization for off-network communications. ProSe devices in network coverage may also use this synchronization signal to enable communication between ProSe devices that are connected to separate eNB that are not synchronized.
- PSDCH – is used for discovery and is not a primary part of the current investigation
- PSCCH – provides the control channel that describes the format of the shared (data) channel and defines where in the time and frequency resource matrix that data will be sent. Decoding of the control channel is required to decode the PSSCH.
- PSSCH – provides data transport

5.1.4.1 Interference Free ProSe Coverage

In order to compare coverage for a best-case scenario, ProSe can be configured for best sensitivity that can deliver the coded audio stream as recommended by the 3GPP standards. In setting this optimum operating point there two primary parameters to jointly optimize, while holding data throughput at ~13 kbps as required by the recommended AMR-WB audio codec. First, the modulation and coding scheme directly tradeoffs data throughput and against required SINR with lower throughputs requiring a lower SINR to process the receiver signal. Second, the number of resource blocks used for transmission is also directly controllable. By example a transmission with 6 resource blocks has a 3 dB higher spectral density than a signal using 12 resource blocks. Figure 5 illustrates selection of an optimum selection of resource blocks and modulation coding scheme for transporting voice. As shown an SINR of -2 dB is

[12] In this context, limited dynamic range includes filter selectivity limitations in rejecting adjacent energy, receiver phase noise limitations commonly called reciprocal mixing, and non-linear effects like blocking or intermodulation.

enough to provide acceptable audio performance.

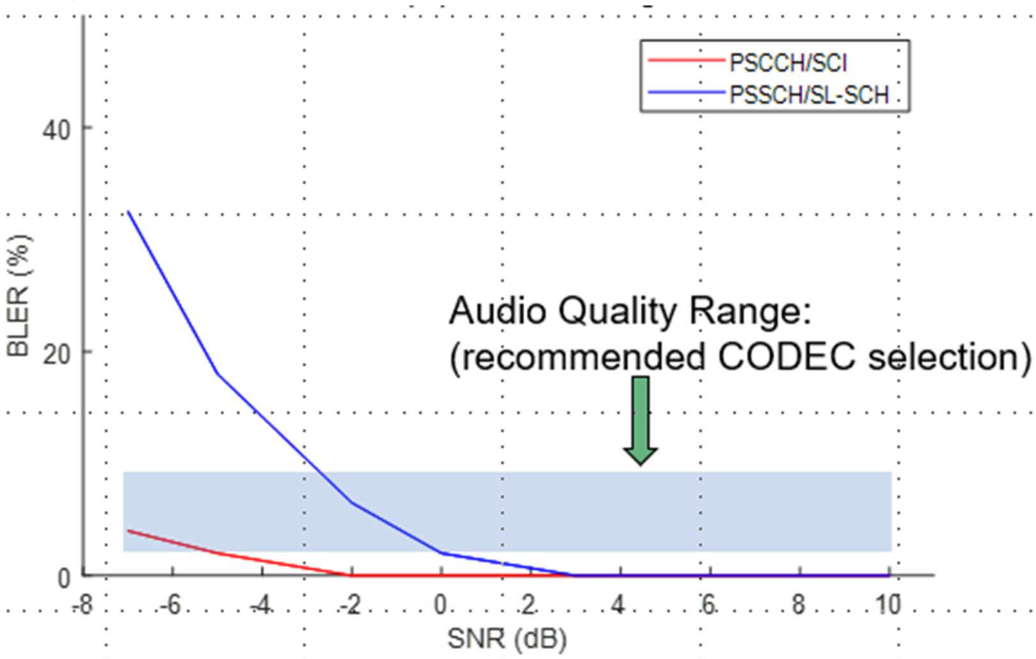

Figure 5, ProSe BLER in EPA5 Fading

The required SINR may then be used as a basis for comparing maximum RF losses between LMR direct communications and ProSe configured for best coverage of coded voice. Figure 6 illustrates how P25 compares with ProSe. Typical LMR radios transmit with 3 watts (35 dBm) of RF power. This signal is radiated by an external antenna on the top of the radio with relative efficiency. By contrast, ProSe typically has a transmitter power of 0.2 watts (23 dBm) and is generally configured with internal integrated antennas that typically have an efficiency of about -4 dBi. ProSe can partially make up this deficit in radiated power by using diversity reception, a wider bandwidth, and linear waveforms. However, the net effect is that ProSe is expected to have a coverage radius that is only 1/3 of LMR P25. A high-power UE (HPUE) has been defined by the standards, that increases transmitter power to 31 dBm. Expected coverage improves to about ½ the coverage radius of P25.

About half the coverage deficit in dB's may be attributed to differences in the expected antenna. While LMR devices typically use external whip antennas, LTE device universally use integrated antennas with much poorer efficiencies. For in network coverage, that is usually capacity limited the esthetic of no protruding antenna has won out over better antenna efficiency that would only provide benefit in fringe RF coverage. However, a primary use case for ProSe is out of coverage communications with a group of devices. Direct communication RF loss is much higher because both the transmitter and receiver are presumed to be within local clutter at low elevation. Furthermore, the loss in antenna efficiency for direct communications effects both the transmitter effective radiated power and the receiver effective sensitivity. Additionally, choosing a low rate voice codec such as P25 AMBE reduces the coverage gap.

Consequently, direct communication developers should consider, portable HPUE development, tradeoffs in deploying more efficient antennas, changes to the waveform design to improve coverage in low noise environments, and voice codec selection. Furthermore, data services presumed to require data rates faster that coded voice will have more reduced coverage. In calculating the coverage capabilities for ProSe it was configured for best sensitivity in transporting coded voice. Applications like still images or video require much faster data rates and consequently will require higher transmissions bandwidth and higher modulation coding schemes. Both of these methods of improving throughput have a direct effect in reducing coverage.

	P25 Portable	Portable	HP-UE Portable
Nominal Tx Power	35	23	31
MIMO	1x1	1x2	1x2
Rx Effective IF Bandwidth (kHz)	6	360	360
Rx Noise Figure (dB)	6	7	7
Faded Performance Threshold DAQ3.4 (dB)	17.7	-2.2	-2.2
Maximum RF Coupling Loss (dB)	147.5	136.6	144.6
Antenna Efficiency. (dB)	0	-4	-4
Maximum Link Loss	147.5	128.6	136.6
Radial Coverage Relative	1.00	0.34	0.53
Area Coverage Relative	1.00	0.11	0.29

Internal antenna

Figure 6, Relative Coverage of P25 and ProSe

5.1.4.2 SLSS/PSBCH

The ProSe waveform may be partitioned into different signals. The following sections described these signals and make recommendations.

To establish communications or discovery the ProSe receiver must first acquire time and frequency synchronization with potential transmitters and obtain essential parameters. For ProSe devices exclusively using the network as a synchronization source, all required information is provided by the LTE downlink including: the primary synchronization signal (PSS), secondary synchronization signal (SSS), the PBCH, and MIB/ SIB information. Network synchronization is well established, should be used as the highest priority synchronization source, and is not part of this investigation.

LTE-direct devices may also receive synchronization information from other LTE-direct devices via the Sidelink Synchronization Signal (SLSS.) Like the network synchronization signals the SLSS consists of a primary synchronization signal PSSS (Primary Sidelink Synchronization Signal) and a SSSS (Secondary Synchronization Signal). The PSBCH (Physical Sidelink Broadcast Channel) is also co-located within the same sub-frame and contains parameters describing the configuration and the state of the Sidelink.

ProSe devices that broadcast the SLSS are known as synchronization sources. A ProSe device broadcasts the SLSS either as a synchronization source that periodically transmits SLSS/ PSBCH to provide a synchronization service to the surrounding area known as a synchronization beacon (SB) or it may also transmit SLSS/ PSBCH when it has a message to transmit during the same PSCCH period. All transmissions of SLSS/ PSBCH may be used by other ProSe devices for synchronization maintenance purposes.

A typical environment for ProSe synchronization, illustrated in Figure 7 demonstrate several different synchronization scenarios.

- Device (A) is in network coverage but receives a ProSe message from device (B). Device (B) transmits its message to device (A) with synchronization associated with its serving eNB. Device (A) served by a separate, potentially asynchronous eNB, accepts ProSe synchronization from device (B).
- Device (C) receives network synchronization from its serving eNB and operates as a ProSe SB with timing based on network synchronization. Additional ProSe devices may use device (C) for ProSe synchronization including devices that may act as SB’s.
- Device (D) operates as an autonomous SB and uses its internal reference as a basis. Its internal reference may be locked to GNSS if available.
- Device (E) is in reception range of several synchronization sources. Therefore, signals based on these sources or even on a source not previously detected should be decoded by the device. Devices may have implementation limits on the number of separate synchronizations they are able to decode. As a collective, devices may therefore want to take actions that minimize the number of synchronization sources with different timing.

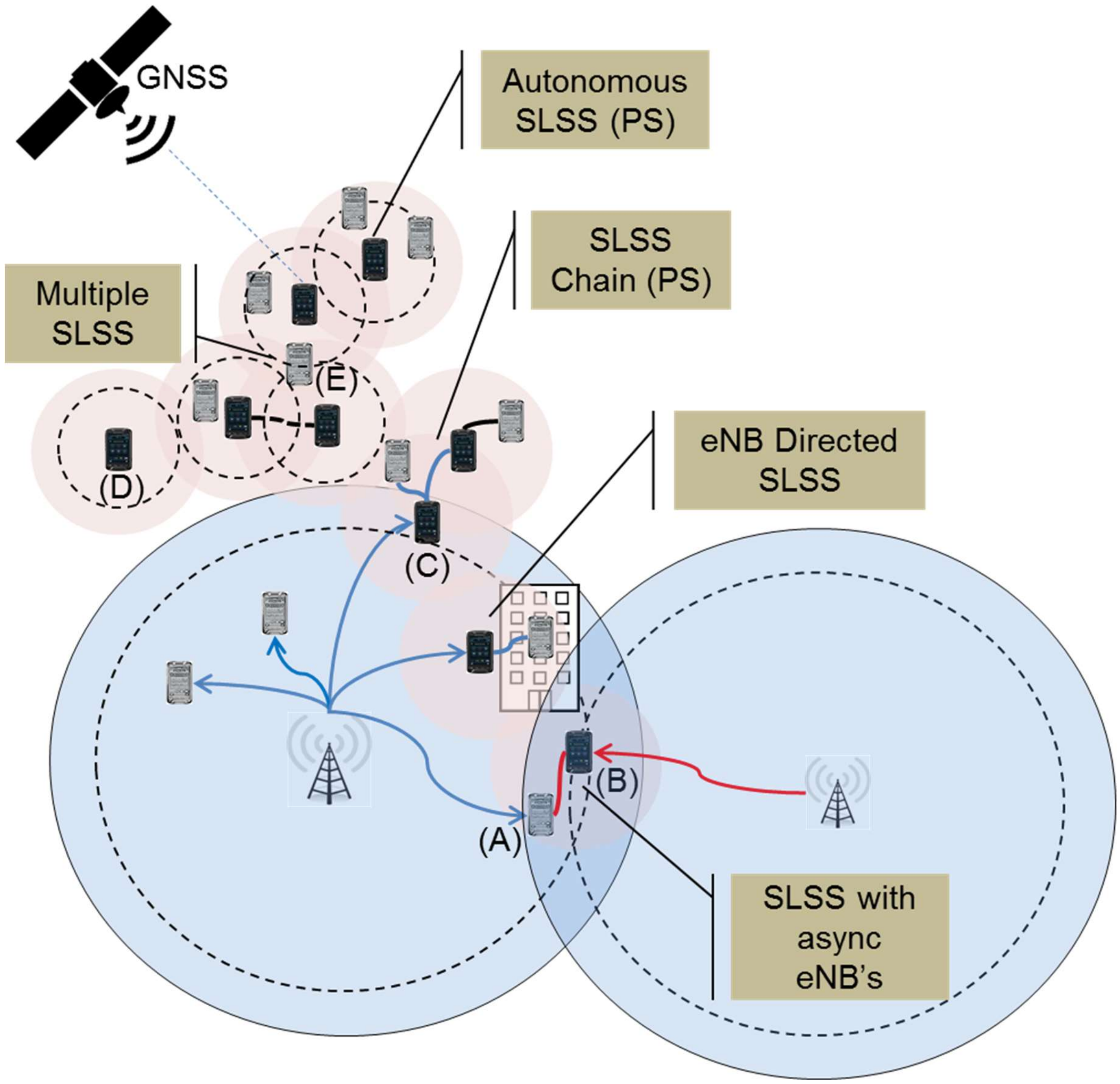

Figure 7, Typical ProSe Synchronization Environment

The final bullet demonstrates a requirement for a receiving ProSe device to handle reception associated with multiple synchronization sources. Several issues result from this conclusion:

1) The ProSe UE should be able to decode multiple synchronization signals including those that may occur with similar timing. For purposes of this statement multiple transmitters sending the same synchronization information with enough time alignment to be unresolvable would be considered a single synchronization signal but might later bifurcate due to reference precession or physical movement. Similar timing, but different ID's or BCH content would be separate synchronization sources.
2) For multiple reasons ProSe UE may not be able to decode all available synchronization signals each PSCCH period.
    a) Half Duplex – ProSe transceivers are half duplex. A device that is transmitting will miss all signals that are sent.

b) The dynamic range of concurrent signals may exceed the processing dynamic range of the receiver. For example: typically, the strongest signal captures the receiver AGC. Weaker signals are suppressed by the ratio of the dominate signal to the weaker signal. Smaller signals will be expected to have a lower SINR associated with their smaller amplitude and higher relative noise processes due to linear dynamic range limitations of the receiver.
c) Each signal including synchronization signals are subject to signal fading or shadowing by obstructions in the RF propagation path.
d) Multiple synchronization signals with similar or the same configuration may arrive with time skews that are small enough to prevent separate discrimination.
e) A practical implementation will likely limit the number separate synchronization sources tracked.

3) A ProSe UE benefits from tracking synchronization sources across multiple PSCCH periods. Tracking synchronization sources provides a mechanism to manage finite processing resources and battery life. For instance, a device might limit the number of synchronization sources based on an operational requirement that a device operate without a battery swap out for a complete work shift.
   a) New synchronization should be accepted quickly but be removed only after a protracted period without detection, because the synchronization has been combined with another, or based on priority mechanisms when synchronizations must be pruned to device limitations.
   b) Synchronization sources can be categorized as adaptable or fixed sources. A fixed synchronization source has a basis for its timing that cannot be changed by the ProSe modem. Examples of a fixed basis would be networking timing, GNSS based timing that uses a fixed mapping between PSCCH periods and UTC, and any other basis that is supplied to the ProSe modem as fixed. Adaptable synchronization sources do not have a direct connection to a fixed synchronization source. Consequently, aligning adaptable sources with fixed sources and with clusters of adaptable sources may provide performance benefits. Some adaptable sources may choose synchronization based:
      i) on their internal reference because no acceptable external references are detected
      ii) on GNSS but not use a fixed mapping between PSCCH frames and UTC
      iii) on detecting synchronization references, but the detected references are not known to be fixed.
   c) ProSe devices should work in a distributed fashion to reduce the number of adaptable synchronization sources by providing mechanisms to shift timing toward preferred fixed synchronization sources or toward shared timing for clusters of devices with no fixed sources.
4) The ProSe UE should perform reception processing for each synchronization source that it is tracking.

5.1.4.2.1 Synchronization Beacons

Synchronization Beacons (SB) are periodic transmissions of SLSS/ PSBCH from a subset of ProSe devices even if no data needs to be sent. Devices may be configured to act as SB's, may become a SB based on not detecting a suitable SB already operating in its proximity, or may simply not become a SB. ProSe devices operating as SB's may become the basis for synchronization of other devices that decode the SB. Sharing a common synchronization may benefit devices by reducing intra-system interference, reducing blind signal searches, and establishing priorities for devices with limited processing resources.

As a synchronization distribution system, SB's would ideally be positioned to provide continuous coverage of devices operating in ProSe modes. However, generally portable devices are simply where they are carried, and mobile devices are where they are installed.

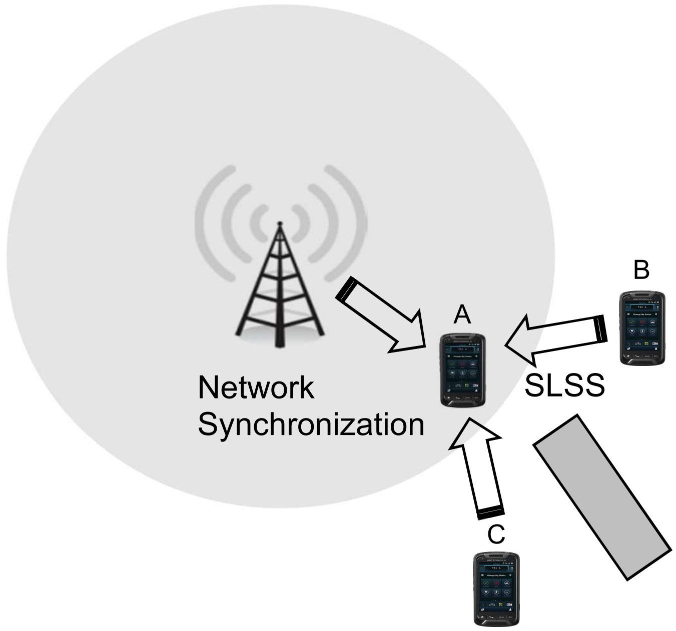

Figure 8, Multiple Synchronization Sources

3GPP deals with this uncertainty by allowing for configured and autonomous SB's. A device may, by network signaling or via configuration become a SB. Other ProSe devices may become SB's based on their RF environment. A device in network coverage compares the signal strength (RSRP) of its serving eNB to *syncTxThreshIC.* If the RSRP is below threshold then it becomes a SB, otherwise it does not. Likewise, a device out of network coverage compares the signal strength of any decoded SB's to *syncTxThreshOC.* If it finds no SB or only SB's with signal strength less than the threshold then it becomes a SB, otherwise it does not. The proportion of active ProSe devices that become SB's depends on the signal strength of decoded SB's and the thresholds that are configured. For a given threshold, dense clusters of devices will have a small percentage of devices that become SB's based on the RF environment. While in sparse device environments a much higher percentage of devices may become SB's.

The standard provides the flexibility to assign *syncTxThreshIC* and *syncTxThreshOC* levels but does not provide any guidance. Thresholds set for very high signal levels, will result in a larger proportion of devices in a given environment becoming SB's because few detected SB's will have the necessary signal strength to exceed the threshold. At the opposite limit where the threshold is set very low, nearly all detected SB would exceed the threshold and therefore the detecting devices would not become SB's. The optimum settings of *syncTxThreshIC* and *syncTxThreshOC* are dependent upon several factors.

The 3GPP standards implicitly suggest a single decoded SB is selected and is then used as the basis for SB timing. However, the ProSe system should benefit from SB that work collectively to minimize the number of separate synchronization sources.

5.1.4.2.2 Separate Synchronization Sources

Synchronization sources are transmitting devices or eNB that provide a synchronization signal. ProSe devices sending PSCCH, PSSCH, or PSDCH precede these virtual channels with SLSS/ PSBCH and are therefore synchronization sources. Networks send periodic synchronization and are therefore synchronization sources. SB's are ProSe enabled devices that send out periodic SLSS/ PSBCH without necessarily sending PSCCH, PSSCH, or PSDCH.

The 3GPP standards define prioritizations of synchronization sources, but do not clearly define how priority should affect device operation. For some use cases the role of priority is clear, while for others implementation presumptions may be required. The standards appear to implicitly presume that a single synchronization source is maintained by a device and that prioritization is simply selecting the highest priority source. However, Figure 8 illustrates a simple example that shows that multiple synchronization sources may exist. Device (A) receives network synchronization and ProSe synchronizations from devices (B) and (C.) As depicted devices (B) and (C) are each autonomous synchronization sources. For device (A) to decode network communications or ProSe communications from devices (A) or (B), it must establish synchronization for each source. For network communications, synchronization is established before communications can occur. For ProSe, SLSS/ PSBCH is included with message carrying channels during a communications transmission. The ProSe transmission may be synchronized to a SB or may be asynchronous. Furthermore, even if the transmission is based on a SB, it may be asynchronous to a ProSe receiver that has never decoded that SB. For ProSe to achieve mission critical capability, it must be able to handle synchronization from multiple sources.

5.1.4.2.3 Synchronization Source Priority

Synchronization source prioritization in ProSe 3GPP standards recognizes 3 levels with diminishing priority. Synchronization signal content identifies each type:

1) Synchronization directly obtained from network synchronization has highest priority for ProSe operations.
2) Synchronization based on SLSS/ PSBCH received from a ProSe device that is network synchronized has secondary priority.
3) All other synchronization sources have tertiary priority in the 3GPP standards.

While the standards define synchronization source priority, they do not define how it should be used.

Additional prioritization makes sense. Some of these sources could be based on absolute sources and may have a range of differing root synchronization sources.

a) A ProSe device discovers an acceptable SB, with signal power that exceeds the signal threshold for acting as an SB.
b) A ProSe device does not discover any acceptable SB and establishes its own arbitrary synchronization based on its internal reference. The internal reference is subject to frequency error that may affect some processing. The frequency error also produces time precession of the synchronization source relative to other sources. The device transmits as a SB.
c) A ProSe device decodes a SB that that has a power level that is below the *syncTxThreshOC. It may use the SB time and time/ frequency as a synchronization basis for its own SB transmissions.*

d) A ProSe device does not discover any acceptable SB but is synchronized to GNSS. It establishes time arbitrary synchronization. However, GNSS eliminates time precession due to frequency tracking of the device internal reference. The device transmits as a SB.
e) A ProSe device uses GNSS to establish synchronization based on mapping between UTC time and ProSe timing. 3GPP V2X standards establish such a mapping and could be used when GNSS is available.

Synchronization priority may be used as one factor effecting the selection of the synchronization source for communicating.

5.1.4.2.4 GNSS

GNSS capabilities in commercial communication devices is nearly universal. When available, it can provide highly accurate synchronization between communicating network nodes and devices. GNSS is commonly used to synchronize eNB, however 3GPP standards do not dictate a relationship between UTC time and LTE ProSe framing. Different networks may have different mappings between UTC time and LTE framing. The standards for ProSe likewise do not provide a mapping between UTC time and LTE framing, but such a mapping is provided within 3GPP V2X standards. Therefore, while staying consistent with ProSe standards GNSS may be used in the following ways:

- GNSS may be used to accurately match ProSe device frequency references to GNSS synchronization. This method ensures that ProSe radios are centered on their band allocation and that timing references do not drift over time.
- A ProSe device with GNSS service and no network or SB detected may autonomously transmit synchronously to other devices based on a UTC time to LTE frame mapping that may either be configured or previously detected. This mapping can use the mapping from V2X standards to ensure that autonomous SB's with GNS coverage will be synchronous within RF propagation tolerances.
- A device temporarily out of GNSS coverage benefits for a limited amount of time from its prior GNSS synchronization and may benefit from other nearby devices that still have GNSS.

5.1.4.2.5 Message priority

As a mission critical protocol, message priority is essential in handling communication systems that may be congested. Like network operations communication priority may be addressed at the application level, at the protocol level, and at the network access level.

Prioritization can now be defined for various use cases:

- A device decides whether to track a decoded synchronization source
- A device selects a synchronization source as the basis for a transmission
- A device updates its synchronization tracking to reduce the number of separate synchronization sources.
- A device lowers its energy consumption by limiting synchronization searches to certain windows in time.
- Unlikely scenario perhaps – SLSS/ PSBCH not detected, but message bearing virtual channels are active.

Synchronization is provided by the transmitting device, but may also have already been detected via SB, but synchronization may be first established during the PSCCH period that contains a message. Devices (B) and (C) may be acting as synchronization beacons. Then device (A) will detect the SLSS/ PSBCH signals and track these synchronization sources. At some later time, devices (B) and (C) may transmit messages. Device (A), in performing receiver processing for each of its tracked synchronization signals, detects and decodes messages from devices (B) and (C.) In a similar fashion device (A) might transmit a message. Device (C) should detect and decode this message from device (A.)

Devices (B) and (C) may not be operating as synchronization beacons and may be receiving synchronization from another device not illustrated or may have their own autonomous synchronization. In this case device (B) or (C) may transmit a message that is preceded by SLSS/ PSBCH. Detection of this first transmission of SLSS/ PSBCH is usually required for subsequent decoding of the message. Message decoding may be successful without SLSS decoding because an existing tracked synchronization source in device A happens to have similar time and frequency synchronization and fortuitously acts as a proxy. Device A may also miss a first SLSS/ PSBCH because of reception limitations outlined including: half duplex operation, interference, RF fading, AGC capture, and to many synchronization sources.

An important component of reliable communication with ProSe is the distribution of synchronization among ProSe devices. Network devices use PSS and SSS to establish synchronization. The eNB downlink signal sends these signals twice per frame allowing devices to establish and maintain network synchronization. Synchronization with other eNB is only required before handover or in certain dual connectivity scenarios. In ProSe, distribution of synchronization is more complicated.

- ProSe devices may act as synchronization beacons that periodically send SLSS/ PSBCH
    - In network devices may act as SB’s for out-of-network ProSe devices.
    - Out-of-network devices may act as SB’s
- Less commonly, ProSe devices may also be in an area served by separate eNB that are not synchronized. For normal network operations the UE will be served by one of the eNB and might handover to the other thereby switching its timing. For ProSe operations multiple cases exist:
    - A device may process and detect synchronization signals from both eNB’s and pass this information to ProSe for tracking.
    - In addition, the ProSe device may receive SLSS/ PSBCH from in range ProSe devices that are attached to either of the local eNB.
- The ProSe device may receive SLSS/ PSBCH that has no direct affiliation with network timing.

A ProSe device may track several synchronization signals, and then must establish how each is used by the ProSe device. 3GPP standards provide some guidance by establishing that network synchronization signals have the highest priority followed by SLSS that are directly tied to network synchronization followed by other SLSS. Other mechanisms to further prioritize synchronization sources are left to implementation. Furthermore, the standards do not make clear what is meant by prioritization of a synchronization signal. The following are all potential uses for prioritization of synchronization signals:

1. Limiting the number of separate synchronization signals that are tracked by a device.

2. Limiting the number of separate synchronization signals used in receiver processing to search for messages.
    a. Managing processor limitations
    b. Extending battery operation
3. Identifying which synchronization signals may be transmitted as synchronization beacons.
4. As one factor in determining which synchronization signal will form the timing basis for transmission of each message.
5. In congested environments preferentially scheduling higher priority messages.

5.1.4.2.6 Synchronization Sources

The number of synchronization sources that need to be tracked?

Network synchronization tracking is well established and is not included in this analysis. ProSe operation is not anticipated to place additional burden on network synchronization processing. However, ProSe operations that are using network synchronization are subject to handover. Predominately, the serving and destination eNB's are part of a synchronized network. Devices synchronized by the network can anticipate small shifts in frequency and time associated with handovers. Handovers are presumed to be asynchronous events relative to the ProSe PSCCH period. Therefore, network timing can change but the ProSe device may choose to select synchronization sources at the beginning of a PSCCH period and maintain them for this period. This behavior ensures that SLSS, PSBCH, PSCCH, and PSSCH are all based on the same synchronization reference. Frequency changes are limited to the relative doppler shift between the eNB's and the UE. A worse case geometry would be the UE following a path directly between the two sites that would result in a total doppler[13] of about 140 Hz in the 700 MHz band. This change in frequency is expected to have little effect on ProSe performance. Especially as the shifts occur between PSCCH periods. Timing shift due to time differences in RF propagation from synchronized eNB's could be large enough to effect decoding performance. Decoding performance is materially affected when timing is shifted by a significant fraction of the CP (cyclic prefix). This type of problem can be minimized by detecting a change in timing (when present) and maintaining both synchronizations for an overlapping period. In the more unusual case were eNB are not synchronized, timing offset may be fixed or precess between serving sites. A worst-case condition would be that handover occurred near but after the PSCCH period boundary. Transmissions would still be received based on the SLSS timing sent before the message. Acquisition of the new serving eNB timing could be delayed by a PSCCH period but is not expected to materially affect ProSe performance. Network synchronization and passing of serving site information is expected to be enough to enable robust ProSe communication using network synchronization. A UE near handoff is most likely able to track both the serving and destination eNB. The ProSe device may simply perform reception for both synchronization sources.

Using SLSS for synchronization requires more maintenance of multiple synchronization sources. In principal there is no limit to the number of synchronization sources possible, but practical limits need to be applied as reception processing requirements increase in direct proportion to the number of synchronization sources. From a standards perspective a ProSe device in network coverage may become a SLSS beacon by command or configuration. Out-of-network ProSe device may also act as beacons based on the signal strength of SLSS decoded. The 3GPP standard specifies that if a device

[13]Doppler of: $f_0 2v/c$; V = 20 m/sec.

receives SLSS above a configurable signal power level[14] then it may use those sources as time and frequency synchronization sources and does not need to become a beacon. If, however, the SLSS are below threshold then the device should become a beacon. The standard conveys this requirement in the singular sense and does not address behavior when multiple SLSS may be decoded and tracked. The intent of the standard is clear, a device that decodes a strong synchronization signal may use it for synchronization and does not need to automatically become a beacon for its proximity. A device receiving a weak SLSS may also use it for synchronization but benefits its proximal area by providing a beacon signal.

The proportion of active ProSe devices that become beacons depends on the strength of RF links between devices. In relatively dense clusters of devices a small percentage of devices presumably become beacons, while in sparse environments a much higher percentage of devices may become synchronization source beacons. The standard provides the flexibility to assign the syncTxThreshIC level. Set for very high signal levels, statistically nearly all detected SLSS will fail the threshold test. Accordingly, these devices would become synchronization beacons. At the opposite limit where the threshold is set very low, nearly all tracked synchronization sources would exceed the threshold and would not become synchronization beacons. The optimum setting of syncTxThreshIC is dependent on the density of devices and is related to the number of separate synchronization sources.

Reducing the number of separate synchronization sources for tracking and reception has multiple benefits. Power consumption of a UE is directly affected by the amount of processing that is required for reception. Each synchronization source must be detected and tracked during each PSCCH period. In addition, receiver processing of at least the control channel must be performed for each synchronization source. Performance particularly in congested environments is also improved with fewer synchronization sources. ProSe devices operating with the same synchronization source can more effectively monitor activity on the channel and share the available resources. Separate synchronizations may precess through each other's allocations resulting in additional interference to ProSe and to network operations. Finally, additional processing required for multiple synchronization sources requires more processing energy that quickly depletes portable device batteries.

Asynchronous synchronization sources reduce the overall performance of ProSe; an overall synchronization strategy to lower the number of asynchronous sources is highly desirable. This goal may be achieved by controlling the birth rate of new asynchronous sources and by coalescing existing sources.

The timing basis for synchronization sources has two primary forms adaptable and fixed. For these purposes network timing is always considered fixed. Likewise, a ProSe device receiving network synchronization and transmitting a beacon based on network timing is fixed. GNSS timing could be fixed or adaptable according to whether it uses an absolute mapping between UTC and ProSe frame timing[15]. Other synchronization sources are considered adaptable. That is their timing is arbitrary and therefore can be brought into alignment with other references to reduce the number of synchronization sources.

Recommendation for tracking of synchronization sources:

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[14] syncTxThreshIC – signal power threshold to initiate acting as a beacon synchronization source

[15] Such a mapping is providing in V2X standards and could be adopted for ProSe. (36.331 5.10.4)

- In coverage: 3 network sources – Handover regions commonly have 3 similar strength eNB's. The worst possible case is that all eNB's are using separate synchronization timing which would be highly unusual in a fixed network. However, a tactical or deployable network could have conditions in which eNB synchronization was not achieved. Each eNB could be a synchronization source for ProSe capable devices. Therefore, a ProSe device should be able to track up to 3 network-based sources.
- GNSS share a common absolute time reference. However, ProSe standards do not include a mapping between UTC and ProSe framing. Therefore, ProSe devices using GNSS may not be synchronized. Devices may be configured to be adaptable or have fixed timing according to whether they user a standardized relationship between GNSS time and ProSe framing.
- Other sources may be treated as adjustable. Figure xxx illustrates an example geometry that may support multiple separate synchronization sources. RF signal barriers may exist in outside conditions and within structures.

{!REQUIREMENT – ProSe devices should track up to 3 network synchronizations.

{!REQUIREMENT – ProSe networks should adopt the relationship between GNSS based UTC and the frame timing specified for V2X.

{!REQUIREMENT – ProSe device that are not synchronized to an absolute reference should support adjusting their timing based on received synchronization signals with the goal of reducing the number of separate synchronization sources.

5.1.4.2.7 Synchronization Source Mangement

Mechanisms to reduce the number of separate synchronization sources are not addressed in 3GPP standards. From all the possible ProSe transmitters in range of a ProSe receiver a separate synchronization source needs to be defined for each SLSS/ PSBCH signal that has been decoded and cannot be combined with another synchronization source. Differences that prevent combining include: timing skew greater than ¼ to ½ of the active CP, significant frequency errors, different SL-ID, and different PSBCH content. Synchronization sources may be in a constant state of flux particularly with moving devices:

- A receiving device may decode multiple synchronization sources
    - Existing synchronization sources
    - A new synchronization source for the first time
        - A device transmits for the first time in range of the receiver
            - New source due to device movement
            - New device as first transmission after ProSe enabled
        - Differences in device frequency references cause time precession resulting in an apparent single source splitting into two
        - Movement causes a single source to split into two due to time skew
- Life cycle events – synchronization sources are tracked over long periods relative to the PSCCH period and likely are not detected during every PSCCH period
    - Authenticating synchronization sources include PSSS, SSSS, and PSBCH signals. Detection of PSBCH may be used to authenticate a synchronization source. PSSS and SSSS may generate false positives in low quality signal conditions.

    - Aging synchronization sources that are not detected for a succession of PSCCH periods may be deleted.
    - Combining synchronization sources that are adaptable reduces the number of separate sources within an area.

5.1.4.2.8 Synchronization Source Pruning

Minimizing the number of separate synchronization sources is highly desired for performance, reliability and battery operation. To minimize differences with and extensions of 3GPP standards, we recommend a distributed approach with minimum required signaling. An approach is described below.

- A ProSe device can track multiple synchronization sources. All tracked synchronization sources should be presumed time adaptable unless a source can be identified as having a basis with an absolute reference. Network synchronization, SLSS with a SL-ID tied to network synchronization, and GNSS synchronization with a fixed mapping between UTC and Sidelink framing are examples of absolute references.
- A ProSe device should adapt its internal frequency reference to high accuracy references including: GNSS and network synchronization. When it does not have a reliable high accuracy reference, it may not adapt it reference, but may track offsets from its reference to decode SLSS.
- Synchronization beacons send out time and frequency synchronization information based on a current estimate for a collective of devices that may include devices nearby.
    - Beacon transmissions occur according to a transmission pattern set by the following considerations.
        - Devices transmitting non-adaptable synchronization sources are likely to receive synchronization signals matching their sources. Non-adaptable sources will not be adjusted. However, these same devices may receive additional synchronization signals that are adaptable, and these will be adjusted.
        - A beacon may transmit more than one synchronization source. For example, a ProSe device based on an absolute reference may attempt to slowly shift additional devices to that reference timing. It's also possible that an absolute reference device could become a SB because it is receiving messages that are asynchronous. The principal idea is that the greater good is served by inducing the asynchronous transmitter to receive the SB and assume its timing for subsequent transmissions.
            - Multiple beacons can be sent out simultaneously and within the same PSCCH period. Gradual reference shifts may not always be necessary. A ProSe device that begins receiving an absolute source may begin using that source and perhaps become a beacon to bring other devices in its proximity to a single reference.
        - The average duty cycle of beacons is a function of their adaptability, their 3GPP priority, and other signal metrics. By example absolute reference may transmit each PSCCH period while asynchronous SB may adopt a lower duty cycle.
        - Transmission of a beacon synchronization signal prevents reception of synchronization signals with similar timing.

- Receiving devices may capture timing, frequency estimates, and decode multiple synchronization sources with each applicable PSCCH period.
    - Network based synchronization signals are tracked and may be used as a basis for adapting other received synchronization sources. These sources are presumed to have a fixed time and frequency reference. SLSS with an SL-ID may also be treated as non-adaptive.
    - GNSS also provides absolute time and frequency references. However, ProSe does not require a specific mapping between ProSe framing and UTC.
        - Based on current standards a ProSe synchronization source does not send any information allowing a decoding device to know that an SLSS is based on GNSS.
            - Therefore, a device receiving a GNSS based SLSS does not know its basis and must treat it like other SLSS.
            - A device that has a reliable GNSS may use it as it as a synchronization source.
                - The device may use GNSS synchronization for calibrating its frequency reference.
                - A device implementation may choose to use the V2X mapping between UTC and ProSe framing; if it does then the device can treat the SLSS as non-adaptive.
                - A device that doesn't implement a fixed mapping should be treated as an adaptive SLSS.
    - Synchronization sources not directly tied to network timing may also be used for adapting timing.
    - A ProSe device may implement an algorithm that attempts to coalesce differing SLSS into fewer separate sources.
        - A ProSe device may use SLSS it tracks as input.
        - The algorithm may weigh SLSS according to signal quality metrics and other configuration parameters.
    - Use an adaptation algorithm that calculates a new time reference that is closer to the collective timing for receiver sources.
        - Detected synchronization sources can be weighted as a function of their priority defined by 3GPP standards and by other signal metrics available to each UE.
        - Adaptation rates should be consistent with tracking rates for synchronization sources and not causing missed messages.
    - Receivers have limited instantaneous dynamic range. As a result, total received power will control AGC action. A dominate received signal will therefore suppress other coincident signals. Suppressed signals may include synchronization signals, but also may include PSCCH, PSDCH, and PSSCH.
    - Adaptable synchronizations may be resolved into separate sources
        - Different SL-ID or separated timing
        - Common SL-ID with similar timing

- A ProSe UE may maintain multiple synchronization instances that may be categorized according to their adaptability as illustrated in Table 4.
- A ProSE UE may receive multiple synchronization updates. These updates are used to update existing synchronization instances or create new ones.
- Synchronization updates need to be mapped to tracked synchronization instances.
    - Absolute references like: (1) network timing, (2) a direct tie to network timing, (3) GNSS with a fixed mapping between UTC and frame timing (PSCCH period)
    - Non-drifting references like: (1) GNSS where there is no fixed mapping between UTC and PSCCH period, but where GNSS can be signaled. (4) Other synchronization signals that do not

Table 4, Synchronization Instance Adaptability

	Non-adaptable Timing	**Adaptable Timing**
Primary / Network Frequency Reference	(1) Network synchronization (2) SLSS based on network synchronization (3) GNSS with fixed mapping to PSCCH period	(1) GNSS with arbitrary time mapping (2) SLSS based on a synchronization chain leading back to a standard reference
Adjustable Frequency Reference		(1) UE based reference that adapts based on reference information it receives from other synchronization sources or GNSS information
Device Frequency Reference	(1) A synchronization beacon without a standard frequency reference, but that does not adapt its timing	

Time to associate a source with a fixed source

Table 5, Decoded Synchronization Types

Update Type	**Indication**	**Standards Based**
Network Synchronization	Sourced from network synchronization of UE	Yes
SLSS based on network synchronization	Based on successful decoding of PSBCH with direct network synchronization SL-ID	Yes
GNSS	Sourced from regular update from GNSS	No, however, V2X specifies a mapping between UTC and PSCCH timing
Asynchronous SLSS	Based on successful decoding of PSBCH without direct network	Yes

	synchronization indication from SL-ID	

A UE may use GNSS for frequency reference and timing based on decoded PSBCH.

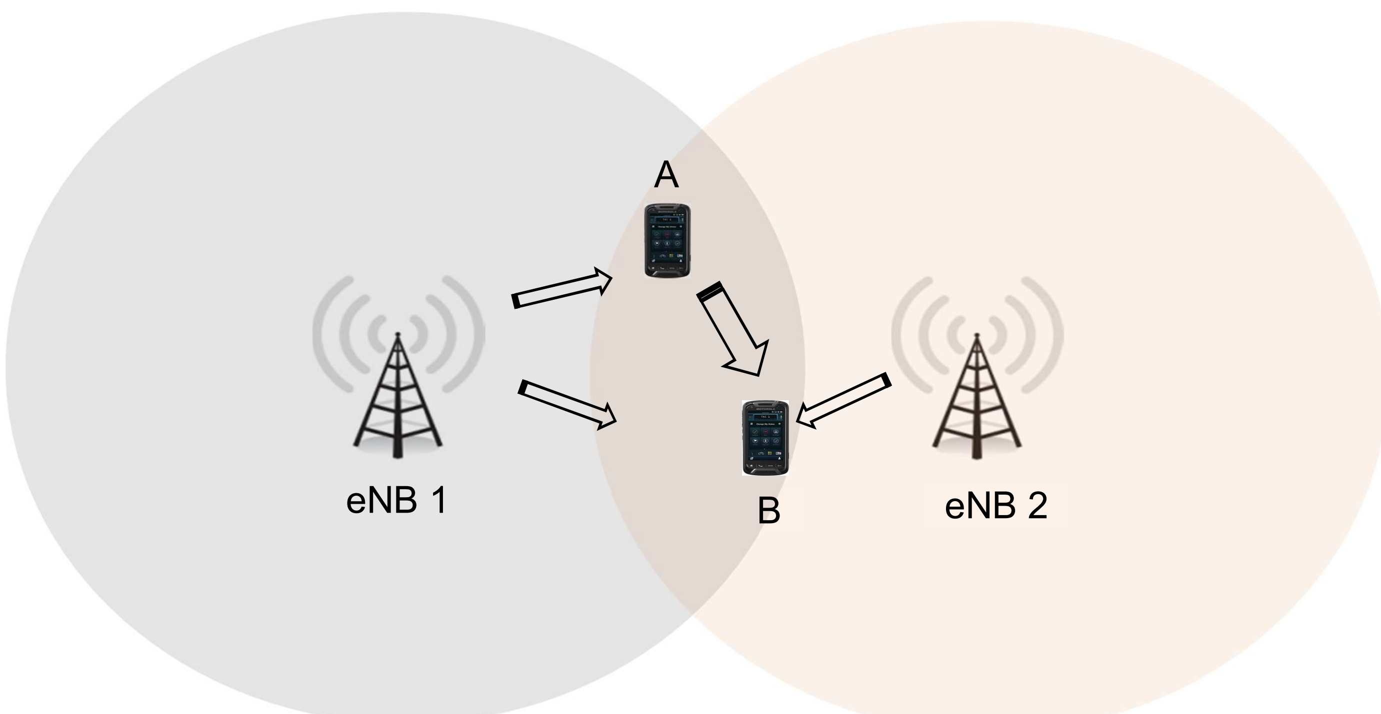
Prioritization of synchronization references

An overall scheme for maintaining synchronization sources includes behaviors defined by 3GPP standards and by additional behavior necessary to provide a highly reliable communication system.

At initialization a ProSe UE begins to search for synchronization sources. The following cases serve to motivate appropriate behaviors. Since, a UE may maintain multiple references simultaneously the cases describe a synchronization instance of a UE. A UE is generally expected to have multiple instances that may be born, track, merge, split, or die. A goal of the collective of devices is to reduce the number of synchronization sources that must be separately tracked by a UE.

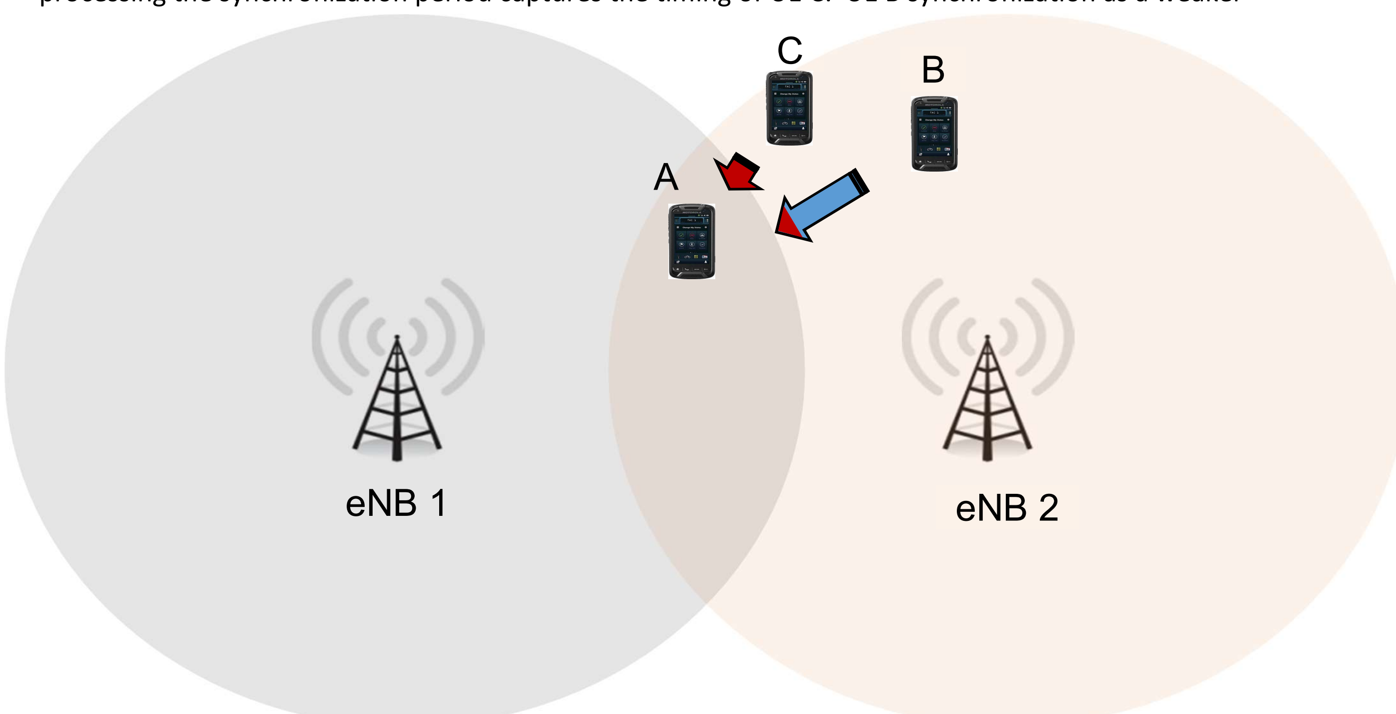
Case 1: Following initialization a UE receives network synchronization

For each network synchronization that is successfully detected and subsequent ProSe related SIB decoded, the ProSe function shall update applicable SIB information from the decoded eNB. PSCCH timing and frequency tracking are shared from UE network processing functions.



A UE may receive more than one network synchronization within a frame. Most commonly, the UE will decode additional synchronized eNB signals in coverage range. Although the eNB are synchronized differing propagation delays can result in significant skew between their relative timing. The UE will know these are separate eNB due to separate identifiers in PSS, SSS, MIB, and SIB. Depending upon the relative delay between received eNB, an UE might track separately, treat synchronized eNB as a single synchronization source for ProSe purposes, or may only be able to decode some network synchronization. In any of these events, an applicable transmitting ProSe UE will transmit SLSS/ PSBCH based on its serving eNB during a PSCCH period in which it is performing either discovery and sending data. A receiving device that decodes this synchronization channel will use its timing for the applicable discovery or data that follow. Since the synchronization channel and the information channels will have followed the same RF path no differential delay is expected between these channels. Figure xxx illustrates this use case. UE A receives synchronization from eNB 1 and uses this timing as the basis for its transmission to UE B that includes: SLSS/ PSBCH and an information channel.

A collision may occur in the synchronization channel that may adversely affect the transmission. As illustrated in Figure xxx, UE B is transmitting a message intended for UE A. At the same time UE C also transmits. It transmission may carry just SLSS/ PSBCH or may also include an information channel. The information channels for the transmissions from UE A and B are not likely to collide because each transmitter selects resources from a resource pool use an algorithm that attempts to minimize collisions. However, the SLSS/ PSBCH occur in a fixed location. Consequently, the synchronization transmissions of UE B and UE C overlap, skewed by the differences in their reference time and the propagation time to UE A. As illustrated UE C is closer and therefore has less transmission loss. UE A in processing the synchronization period captures the timing of UE C. UE B synchronization as a weaker



signal is effectively blocked. If the differential delay between UE B and UE C transmissions is large enough then UE A is unable to process UE B information channels using synchronization from UE C. UE A may still successfully decode UE B messages provided it has a prior synchronization instance that it is tracking. Appropriate synchronization instances could include eNB2 timing or some other SLSS/ PSBCH signal including prior UE B or synchronization from another UE with similar delay.

The amount of differential delay permitted is covered in section xxxx. Typically, public safety communications are group based and many devices are attempting to receive a transmission from UE B.

The synchronization collision as depicted can significantly degrade reliable communication to the group, depending on the tolerance for delay skew between the synchronization channel and the information bearing channels.

Case 1b: Network synchronization: local eNB not synchronized

3GPP standards allow operation where physically adjacent eNB are not synchronized. Network operations and ProSe both benefit from synchronized eNB and therefore non-synchronized eNB is less common in fixed networks. However, operational boundaries in fixed networks and deployable/ mobile networks may not always be able to provide eNB synchronization.

eNB generally use high quality frequency references therefore unsynchronized eNB timing may slowly precess due to the difference between these unsynchronized references. eNB may also be locked in frequency and therefore not drift, but not have the same frame timing. Each condition will typically manifest degraded performance that depend upon the current time offset. Time drift can be treated as fixed for PSCCH periods and therefore both cases have similar behavior for a current time offset.

Typically, the principal repeating structure of ProSe is a PSCCH period of 40 msec. Within each PSCCH period some sub-frames are allocated for ProSe and the remaining may be allocated for network operations. Time offsets comparable or greater than a sub-frame will generate significant interference between network and ProSe operations as ProSe devices will transmit during network sub-frames. Smaller time offsets will require multiple synchronization instances to be tracked by the ProSe receiver. Offsets significantly smaller than a CP can be processed by a single synchronization instance. Given a random uniform distribution of time offsets, harmful interference between network and ProSe operation can be expected.

Case 1: Network synchronization behaviors for reliable communications

Given the potential for interference between network operations and ProSe communications, network operation is preferred under acceptable coverage conditions. Devices may operate in ProSe and network mode coincidently. Therefore, devices and their applications should preferentially use network operations when possible.

{!REQUIREMENT - ProSe enabled devices should preferentially use network operations over ProSe operations.

Synchronization channels are more robust than data bearing channels and consequently may be used when data transfer is not possible. Consequently, UE may directly synchronize to the network, but not be able to communicate with it. These devices would be limited to direct communications.

Since adjacent eNB may not be synchronized, ProSe UE should be prepared to receive communications that are synchronous to any local eNB. This requirement includes eNB that may not be in range of a receiving UE. This condition is illustrated in Figure xxx. Therefore, a message may be sent by a UE that is synchronous to an eNB that is new (untracked) by that UE. Therefore, to process such a message, the UE must be continuously searching for potential new synchronization sources.

Requirement: A ProSe device must continuously search for new synchronization sources in networks that include unsynchronized eNB.

Case 2: Following initialization a UE receives SLSS/ PSBCH with a direct tie to network synchronization

Behavior of SLSS/ PSBCH that is sourced by ProSe UE that have network synchronization has similar timing characteristic to network synchronization. These ProSe synchronization sources are synchronized to the network and therefore do not drift relative to their serving eNB.

Like direct synchronization to eNB, the associated SLSS/ PSBCH signals may not be synchronized and therefore continuous searching is required to prevent missed messages.

Case 3: Following initialization a UE receives SLS/ PSBCH without a direct tie to network synchronization

The standards

At point does a UE update its reference based on SLSS?

The 3GPP standard provides some guidance on the prioritization of

if it To facillitatehe ould easily be large enough to cause probleto Worst case timing would be f is or d is expected to generally be caseypically this means that processing

The number of synchronization sources that should be searched in reception processing?

Tradeoffs in prioritizing synchronization sources for beacons?

Selection of synchronization instance for a transmission?

Effects of congestion on message scheduling.

and then used to search for potential messages can be left to implementation, but some lower bounds are provided here. Adjacent can be placed is it track timingcommunications between unsynchronized dep working presumption is that a ProSe UE will select at most one tracked/ decoded SLSS/ PSBCH as a periodic synchronization beacon. Further, that it will use a combination of 3GPP rules and other criteria to select at most a single decoded synchronization signal for periodic transmission. However, a ProSe device with data to send may associate and use a synchronization signal that correspond with a targeted device or set of devices that may not be the selected beacon signal.

Reception Aspects

Figure 9 illustrates a potential SS environment as seen from the perspective of an UE receiving synchronization signals. As illustrated UE_A is receiving 3 SS, two asynchronous to the network and one to the serving eNB. To receive data traffic from any UE transmitting synchronous to an illustrated SS, UE_A must track all the synchronization sources. UE_A may receive scheduling information directly from the eNB for D2D traffic originating from UE in coverage, but also may receive traffic from UE that are synchronous to the eNB, but are using autonomous scheduling from the D2D resource pools. UE transmitting based on UE_B or UE_C must use the resource pools. Consequently, UE_A must search applicable resource pools for each SS time reference to find applicable control messages. To ensure reliable public safety operation a UE should have the processing resources to process these asynchronous SS, control channels, and the shared channel that may follow.

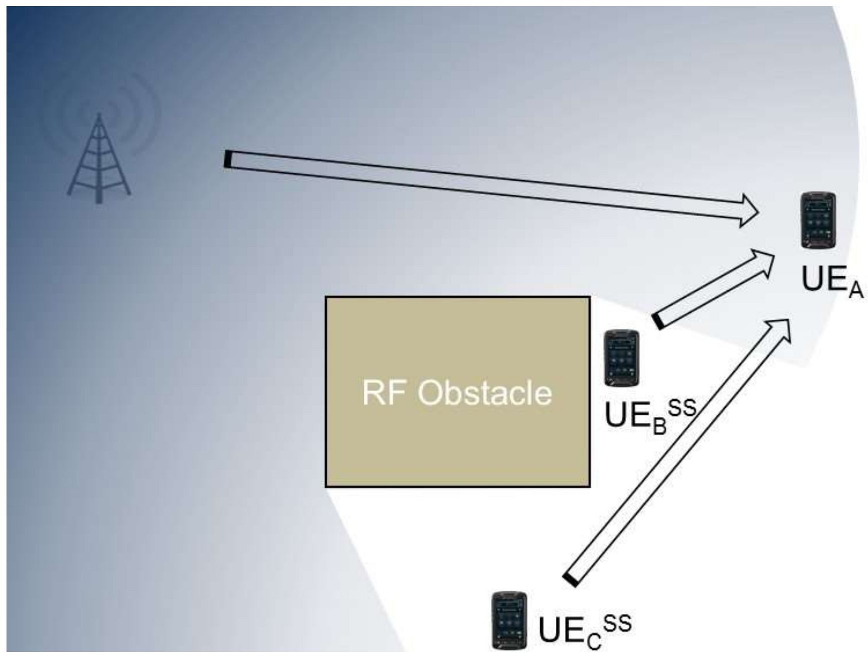


Figure 9, Multiple Synchronization Sources

5.1.4.2.9 Synchronization Sources

3GPP standards allow for multiple SS, but do not define several aspects of SS:

- The life cycle process
    - Birth decisions
    - Death decisions
- The density of SS
- When a SS should be offset from a receiving source

The management of SS is a critical component of reliable LTE-direct communications. While it is possible to configure D2D devices to operate off network without receiving a SS, these devices will operate at a disadvantage in radio performance and battery life. Devices operating without a SS must decode the PSCCH without prior timing and frequency synchronization. This approach is discussed further in the PSCCH section???

Synchronization with SS allows a device to save considerable battery power when it does not have active data sessions. Following synchronization, a device searches its Rx receiver pools for valid control messages. The location of control messages is limited to a relatively small number of subframes within the PSCCH period. Receivers make take advantage of this structure to idle their receivers and processing resources thereby saving substantially on battery life.

As defined by 3GPP standards UE upon initiating D2D operation search for SS. Only three different signals are currently recognized for D2D primary synchronization: direct network using PSS (primary synchronization signal), D2D SS that are broadcast on Sidelink from a UE attached to a network, or other SS that do not have a direct synchronization to a network. Network synchronization using PSS/SSS is well established and is not consider here.

3GPP standards considered and rejected “cluster head” architectures particularly for public safety communications using D2D. In a cluster head architecture, an UE within a cluster of D2D devices acts as the master while other devices operate as slaves. This approach improves resource efficiencies by having a single scheduler that reduces communication collisions. However, the cluster head is a single point of failure that is unlikely to provide reliable communications to a mobile group. The SS as defined can be interpreted to work as a loose cluster head capability and thereby has the same potential weakness. A cluster of devices may share a single SS, but if the serving SS suddenly shuts down or moves out of radio range then the collective must reach a new equilibrium of serving SS, meanwhile reliable communication may be interrupted or degraded. The standards define the initiation of a SS either by command or when a suitable source is not found, but do not define when a SS should be removed. The standard suggests that synchronization should be supplied by a low density of SS, but its structure does not prevent a high density of SS. It further prescribes the priority of SS but does not define how these priorities should be applied. A further consideration is that SS do not have a mechanism to evaluate how other devices may be affected by its absence as a SS.

Battery life is an essential consideration for a practical public safety communications protocol. Significant factors for power consumption include:

- Receiver power consumption during idle periods (no active data transfer)
- Receiver power consumption during active periods
- Transmitter power consumption during active periods

The power consumption of D2D devices can be a strong function of its environment. Power consumption may be based on whether it acts as a SS, what transmitter power it is using, the median quality of received signals (additional error correction is required for poor quality signals). Therefore, battery life requirements should be provided under worst case scenarios for each of these parameters.

Traditional models for voice communications in public safety environments use the 90-5-5 (idle-RX-Tx) rule.

A couple use cases should be considered in considering the best operation of SS.

- D2D devices using network synchronization – D2D devices within network coverage should simply use the available network signal for synchronization. D2D communication within network usually does not require D2D synchronization. An unusual situation supported by the D2D is when devices are within network coverage, but some of the devices are served by separate eNB that are not synchronized. For this case, the device wishing to transmit D2D should initiate D2D SS to facilitate synchronization with D2D receivers. For the asynchronous case, D2D SS may need to be initiated to provide references for receiving devices.
- D2D devices operating as SS that have network synchronization – These devices in effect relay local network timing out to devices that may be operating outside of network coverage. With

propagation delays significantly smaller than the CP, the timing provided by the D2D SS provides an accurate reference for D2D operations.

- D2D SS without a direct tie to network time may operate synchronous (but delayed) to the network or may be completely asynchronous. Synchronization could be the result of a synchronization chain that traces back to a network or could be provided by an absolute reference supplied by GNSS. Asynchronous operation will occur whenever a device does not have an absolute time reference to a network.

Case 1: Operation of an independent D2D network – A group of D2D UE wish to communicate, there is no network synchronization support. As the group assembles initially the first device will not find any other SB and will become a SB. As additional devices arrive each must decide whether to become a SS. The 3GPP standards calls for evaluation of the signal strength of any decoded SS. SS that exceed the configurable threshold do not automatically become SB but could be commanded or configured to do so. In the limit, a very low threshold, results in nearly every D2D devices becoming a SB. For a very high threshold very few devices become SB.

1a: A sparse network of SB provide distributed synchronization for the network of users. This approach is the implicit working presumption of the 3GPP standards. Device are sufficiently clustered relative to the signal strength threshold that only a small percentage of devices become SB. SB devices are likely to be the first on scene. Most new devices arriving in a coverage area already served use existing SS. New devices not finding a satisfactory synchronization source become SB.

This approach can be expected to minimize the total power consumption for a cluster of devices maintaining a synchronization field across the coverage area. However, islands of synchronicity are more likely. In this situation, a device initiates D2D operation and finding no suitable SB becomes a SB. The standard does not define how this device should obtain its absolute synchronization. D2D operation and more generally network operation performance is degraded by the presence of asynchronous D2D communications. Synchronized operations maintain a level of orthogonality between unrelated communications, however unsynchronized transmissions will precess through the timing of other communications. Consequently, it is highly desirable to avoid islands of synchronicity. However, it can be shown that islands become more likely as the relative density of SS decreases. Eventually devices only receive very weak SB and consequently become SB. Fewer islands will exist if devices receiving only weak SB use this weak signal as a basis rather than simply starting a SB that is asynchronous.

Another approach is to allow a very high density of SS.

1b: All devices act as SS for the distributed network

The maximum density of SBS is reached when all D2D devices become SB. This behavior maintains 3GPP standards compliance and simply requires a lowering of the SB threshold or alternatively commanding every device to be a SB. Every initiating device finds proximate SS below threshold and becomes a source. SS may either take on the local synchronization or may be configured to offset reference timing by sub-frames. Offset timing allows a device to receive a SS and then transmit its own synchronization signal in a later frame within the PSCCH period. However, devices operating with different offsets increase power consumption for receivers that must search for additional signal timings. Offset timing also increases the likelihood of collisions between network and other D2D communications because subsequent sub-frames may be mapped to other virtual channels (control and shared.) If new SS devices offset then the potential exists for long chains of offsetting SS. This places additional demands on receivers for searching each SS it decodes for control messages.

SS may also be deployed without offset. This approach requires that devices puncture transmissions to allow enough receptions of in range SS to provide synchronization. Puncturing rates may be adaptive to the local environment. Two isolated devices that need to communicate both send SS. With a random distribution each source punctures its transmission and instead listens for SS. In this isolated case, only the other devices can be heard, but only if it does not puncture during the same PSCCH period. Listening devices should accept the first peak during the correlation process as an update to its time reference. The device may use a filter to create a new time reference based on the update. UE can be expected to have a frequency reference accurate to +/- 1.5 PPM. Under this worst-case condition, time reference drift by 30% of the CP can occur in about 1 sec. To guarantee that time drift remains a small fraction of the CP, a UE should receive a SS at least twice per second. For a 40 msec. PSCCH period SS is scheduled 25 times per second. This sets an upper limit on the puncturing rate at about 90%. At high puncture rates, the UE can more quickly adapt its own timing, but not convey its own. These properties suggest that an improved strategy may be to have UE's adapt their own puncturing rate based on what is known about the quality of their reference in time and frequency. Further devices may modify their reference averaging filters based on an estimation of the quality of their reference. Attributes effecting this behavior include:

- Time errors can become significant within a second for worst case reference frequency errors.
- UE may not be able to estimate their own frequency errors effectively without GNSS.
- A UE with a reliable GNSS signal can lock its frequency very accurately. The frequency accuracy benefits both frequency tracking and slows time reference drift.
- The D2D standard does not explicitly utilize GNSS, however V2X does. In V2X a time relationship is defined between UTC time and frame timing. This allows a UE to establish time and frequency lock independent of the SS. This explicit relationship can be adopted in D2D.
- A UE with GNSS lock may modify its averaging filter to limit modification of its time reference.
- A UE without an absolute time reference like GNSS or network synchronization may allow its averaging filter to allow the time reference to be modified more quickly.

Transmission Aspects

An important aspect of reliable D2D communications is the life cycle process of SS within a communication environment.

SLSS is like the DL synchronization channels of LTE network operations. A primary synchronization signal (PSSS) allows the receiver to acquire time and frequency initialization and in the case to LTE-direct determine whether synchronization is based on a network or that it may be asynchronous to any

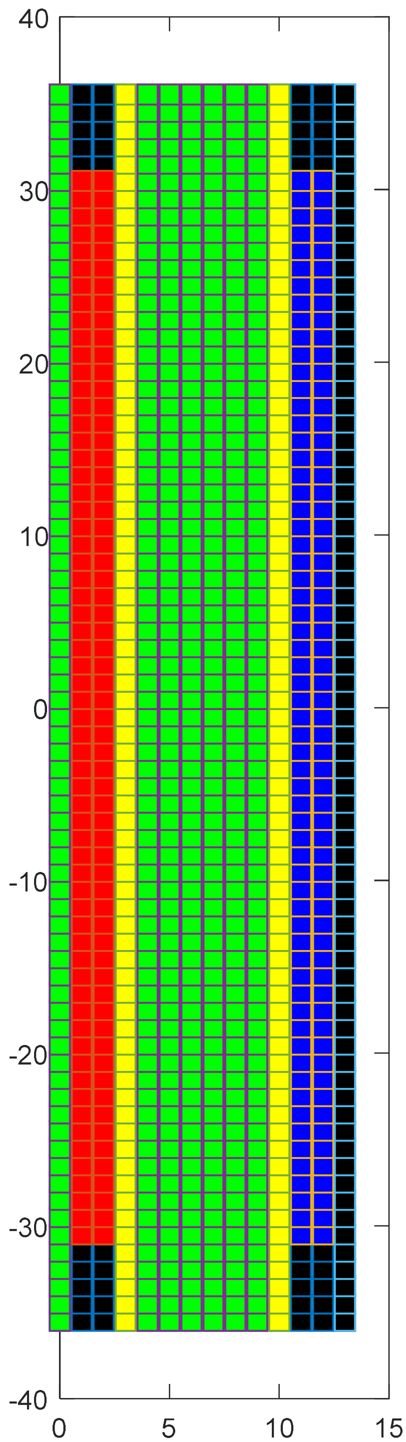


Figure 10, SLSS Allocations

networks. The secondary synchronization signal carries 1 of 168 M-sequence codes. The PSSS and SSSS together determine the SLSS ID in the range of [0: 335]. The SLSS ID defines the scrambling and reference signals for the remaining physical channels. By varying the scrambling of the channels according to SLSS ID, other transmitters that may interfere but that are part of another synchronization group appear as noise rather than coherent energy.

Figure 10, illustrate the allocation of resource elements (RE) to the D2D SLSS/ PSBCH. The PSSS signal shown in red provides initial synchronization. From a signal acquisition perspective, the SSSS shown in blue follows. Acquisition of these two signals provide sufficient information to decode the PSBCH that contains some basic parameters associated with the D2D signals that follow.

The SLSS/ PSBCH is transmitted as the first subframe in a PSCCH period that typically lasts 40 subframes, but may be configured for longer frames. As shown with standard cyclic prefix the subframe consists of 14 symbols and 72 carriers in the frequency domain. The SLSS/ PSBCH is designed to fit into the smallest LTE allocation 1.4 MHz and maintains the same allocations for all defined LTE bandwidths: 1.4, 3, 5, 10, 15, and 20 MHz. PSSS and SSSS only use 62 carriers with the remaining carriers not allocated. The last or 14th symbol of the subframe is blanked to provide an on/ off transition interval for the LTE-direct transmitter and to eliminate interference between network based UE transmissions and LTE-direct transmissions.

SLSS/PSBH is not sent by all LTE-direct devices, but instead by a subset of devices or eNB referred to as synchronization sources. For LTE-direct devices within network coverage synchronization is simply based on acquiring the DL channel and using it as the reference for LTE-direct transmissions. LTE-direct devices out of network coverage may acquire synchronization from other LTE-direct devices that are transmitting the SLSS. Devices that receive the SLSS above an adjustable threshold simply use this signal as their synchronization source and do not become synchronization sources unless configured or commanded to. Those not receiving SLSS above threshold may begin transmitting their own SLSS. Typically, this SLSS is based on any synchronization information it may have available, which may include SLSS signals and GNSS. Synchronization sources basing their synchronization on SLSS typically offset their timing to minimize interference between synchronization sources that have overlapping coverage. A few test cases exist for SLSS performance:

- Network derived synchronization – This case is simply LTE DL synchronization performance and is not evaluated in this study. This case also includes devices using network synchronization, but that may be served by separate, but synchronized eNB.
- Asynchronous networks – Like the former case, devices use network synchronization, but their serving eNB are not synchronized. Consequently, the LTE-direct receiving devices must obtain synchronization from a synchronization source associated with the transmitting device. The network may either configure the transmitting device to….
- Off network device; no SLSS detected – A device that is not able to find a synchronization signal will become a synchronization source.
- Off network device; SLSS found - Other devices that move within proximity of a synchronization source may use this device as their synchronization source. Devices receiving SLSS below threshold also become synchronization sources.

Except for the first case not covered by this study SLSS is required. However, an important observation is that SLSS and PSBCH decoding do not need to be successful for every PSCCH period. Instead the receiver can maintain SLSS/ PSBCH information across multiple PSCCH periods.

5.1.4.3 PSSS

PSSS is designed to enable an LTE-direct receiver to acquire initial time and frequency synchronization. The signal consists of one of two possible sequences that convey whether the source of synchronization is directly tied to a network or may be asynchronous. A UE uses this information in part to determine priority in choosing synchronization sources as a basis for its transmissions.

PSSS provides initial timing and frequency estimation along with whether its reference is directly tied to a network. The PSSS consists of one of two potential 62 bit Zadoff-Chu sequences more fully defined in by [36.211-9.7.1]. A root index of 26 conveys that the SLSS can be directly referenced to network synchronization. Specifically, the PSSS is transmitted from a UE that is synchronized to a network or is a UE listening to a directly network synchronized SLSS but transmitting its own PSSS. All other PSSS use a root sequence of 37 and may be connected via a SLSS chain to a network source or be completely asynchronous to any network.

Simulation of PSSS performance under 3GPP fading profiles with 5 Hz doppler, illustrates the performance of PSSS time synchronization as a function of SNR. A small variance in performance is seen between the EPA, EVA, and ETU profiles which define progressively stronger and longer multipath. Single PSCCH period 95% detection is maintained to about -4 to -5 dB SNR, while the 50% detection occurs between -11 and -12 dB. PSSS is a very heavily coded signal with an effective efficiency of about 0.01 bits/ Hz. This heavy coding provides a certain level of immunity to channel impairments.

For valid time synchronization, the accuracy was required to be within a tolerance of its known value and have a normalized peak above a threshold. This tolerance is consistent with the combined errors associated with estimating timing for LTE-direct.

In the case of LTE-direct three factors were identified as consuming CP margin. First performance degrades for timing errors approaching the CP and dramatically degrades for larger errors. Figure 11 illustrates performance of the D2D shared (data) channel with timing offsets. Each curve on the graph shows the block error rate as a function of SNR for given delay offset. Best performance is near zero offset while offsets above 20 result in degraded performance. The delay offset is in sample delay which consists of about 40 samples per mile of propagation. Therefore, offsets representing more than ½ mile of airlink propagation degrade due to timing offset. D2D operates primarily as a broadcast channel without a tightly coupled HARQ (Hybrid Acknowledgement) process to correct transport errors by directed resends. Consequently, transport error rates must be tolerable to the application. MCPTT voice can tolerate a block error rate of 2% [TR 26.989 Table 5.1.1.6.3.4-1, Media, codecs and Multimedia Broadcast/Multicast Service (MBMS) enhancements for MCPTT over LTE] while maintaining acceptable voice quality.

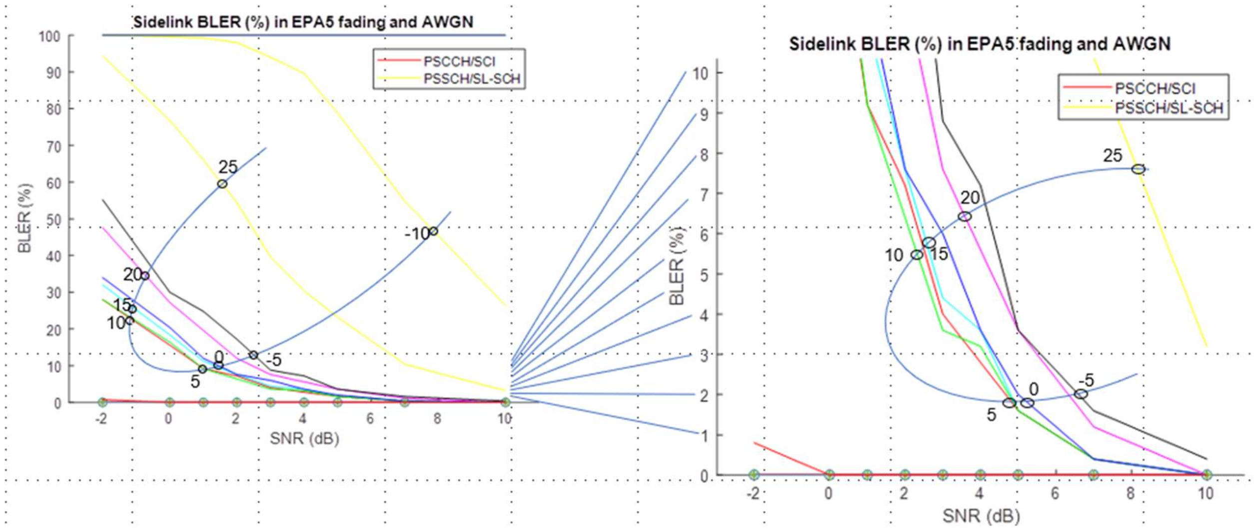


Figure 11, Sidelink BLER as a function time offset

Performance gets worse with more efficient modulations.

Second, unlike LTE network uplink operations that adjust UE uplink transmitter timing to match the round trip airlink delay at the serving eNB, LTE-direct does not. Figure 12 provides an example where propagation delay consumes CP. As shown, unit B acts as the synchronization source for units' A and B. Unit A receives its time reference delayed by d/c. Where d is the distance from unit A to its time reference (unit B). It then uses its time reference to transmit a message that is received by unit C with a relative delay of 2d/c.[16] If d is ½ mile, then the time skew is 5.4 µsec, which exceeds the Normal CP of 4.7 µsec. Without mitigation, a communication range limit can easily be reached due to timing margin.

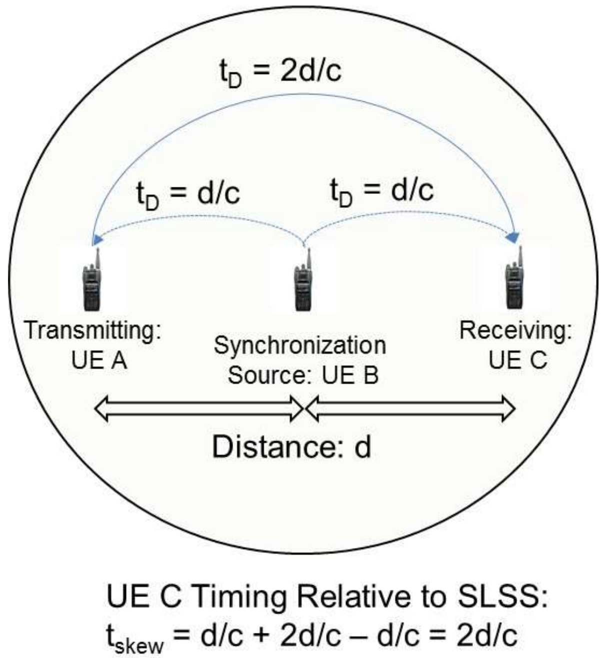


Figure 12, Timing Offset

Range limitations from timing margin are problematic for multiple reasons:

- LTE-direct in general is unconstrained from a user perspective on attempted communications. During a transition period attempts with legacy equipment and LTE-direct equipment would demonstrate an inferior capability particularly in line of sight conditions where distances could significantly exceed the Normal CP.
- LTE-direct performance falls off very rapidly when timing margin is exceeded.
- The user may have a signal strength indication suggesting that signal energy is being received but nothing is presented.

Prediction of communication received signal strength for reliable communications with direct communication are associated with high variances that depend upon local "clutter" and land use at the transmitting UE and at the receiving device. However, when considering timing margin, maximum distance under more favorable conditions should be considered. First responders accustomed to communication challenges know that relocating to a more prominent location can lessen clutter effects and achieve or approach line of sight conditions to other devices[17]. Under this scenario, LTE-direct communication can propagate long distances and easily exceed delays given by the Normal CP. Under these conditions communication will fail.

Third, the multipath propagation channel may consist of a range of multipath components whose extent may consume CP margin. Hess [Handbook of Land-Mobile Radio System Coverage, Garry C. Hess, Artech House, Inc., p 131] provides an empirical formula for estimating the effective multipath delay of a

[16] Units A and B both have the same d/c delay from the synchronization source. Therefore, the time skew relative to unit C's time reference is: t_{skew} = d/c + 2d/c -d/c = 2d/c.

[17] Failing to communicate in apparent line-of-sight conditions is particularly difficult for users to understand and accept particularly when legacy equipment works.

propagation model with multiple delay components. It simplifies multipath profiles to a single number and is designed to be applied to a simplified model including two equal power sources. The first component with 0 relative delay and the second delayed by the Hess metric. Table 6 provides an illustration of the Hess metric for 3GPP models, Winner II and an LMR model. The propagation channels impact on timing uncertainty varies from insignificant to nearly as large as the Normal CP depending on the channel model. EPA, EVA, and ETU are 3GPP delay profile models with progressively larger multipath components. The Winner II model used for 3GPP simulations of D2D is a statistical model that randomly selects multipath delays for each time epoch. An equivalent delay is therefore more difficult to compute, but its extent can be bounded.   Therefore, the equivalent delay for the Winner II B1 model has an upper bound of 240 nsec. [IST-4-027756 WINNER II D1.1.2 V1.2 Winner II Channel Models].   The LMR model is the TETRA HT200 model, which consists of a single secondary component delayed by 15 µsec with a relative power of -8.6 dB. This model was provided as a compromise between P25 CAI performance and the other cellular based models. P25 maintains a 2% BER with a 33 µsec multipath component. [TIA TSB88.1-D, Wireless Communications Systems Performance in Noise and Interference-limited Situations, Part 1: Table 20].

A potential area of further research could attempt to quantify the frequency that long multipath is encountered in realistic D2D situations, particularly where a user might choose to operate from a prominent position.

Table 6, Channel Model Equivalent Delay

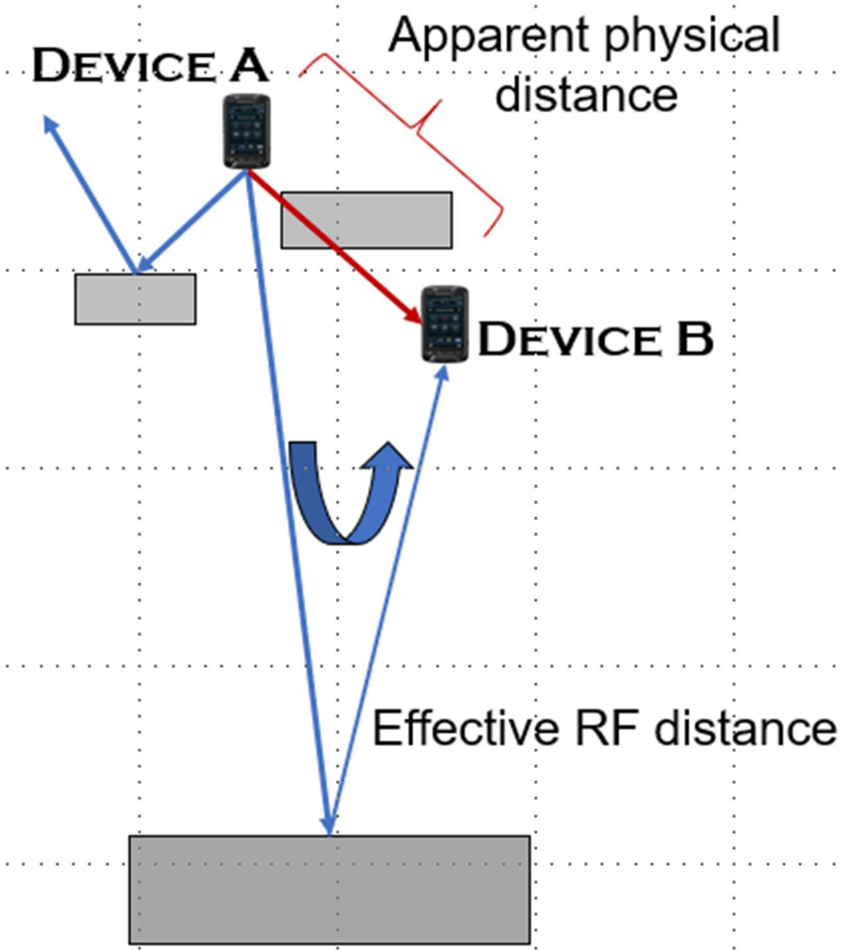
Propagation Models					
	EPA	EVA	ETU	WinnerII	LMR
T_m (nsec.)	88	507	1122	<240	3639

Timing errors in receiver acquisition of the SLSS, airlink propagation delays, and multipath delay spread combine to degrade D2D performance particularly when users establish physically prominent locations for greater propagation distances. Three potential solution to this problem include: using the Extended CP, blindly searching for LTE-direct signals by searching multiple time skews beyond the receiving UE time reference and using the received PSCCH as the time reference.

Based on the data above we can make a few statements about the limitations of using the Normal CP in D2D operations.

If we allocate one third of the CP to propagation delay, delay tolerance, and timing accuracy then D2D operations using the Normal CP are fundamentally limited in range to about 1500 feet.

Public safety scenarios cannot in general be constrained for range that is substantially lower than the RF loss-based range. In fact, based on this analysis public safety LTE-direct operation will need to use the extended CP for many scenarios to ensure that operations are not limited by airlink delays. A communication limit as short as 1500 feet could occur in situations where the apparent distance is much shorter. Figure 13 illustrates a simple example where two devices that are physically separated by a



short distance may have a much longer effective RF path.

Figure 13, Dilation of RF propagation distance

{! RECOMMENDED CAPABILITY – The next generation direct communication solution should support the extended CP.}

{! RECOMMENDED CAPABILITY – The next generation direct communication solution may need to be configured for extended CP to prevent unexpected communication failure due to propagation distances.}

{! RECOMMENDED CAPABILITY – The next generation direct communication solution should deploy receivers that search continuously for messages.

A UE may receive synchronization signals from multiple synchronization sources concurrently which complicates signal handling. A few examples are provided here to motivate proper processing.

Case 1: Single Active Synchronization Source

In the simplest case, a UE receives a single synchronization signal. This signal may be:

- A PSS/SSS signal decoded by a UE that is receiving a network signal.

- A PSSS/SSSS signal that is received by a UE that is receiving a ProSe SLSS that is synchronized to a network.
- A PSSS/SSSS signal that is not directly synchronized to a network.

The decoded primary synchronization signal defines timing and frequency synchronization that simplify secondary synchronization signal decoding. Information from primary and secondary decoding may then be used to obtain ProSe configuration information from either applicable SIB with on network reception or from PSBCH for off network reception.

Case 2: Multiple Synchronization Sources of Differing Type

In a slightly more complex case, a UE may concurrently decode each of the three synchronization signals types bulleted in the paragraph above[18]. The UE should infer that each signal is an indication of a potential set of UE that expect to communicate. Therefore, it must decode PSBCH or SIB information as applicable for each decoded signal. Furthermore, the UE must also perform a separate search for control channel and discovery information for each active synchronization source. In general, each synchronization source will have separate timing, center frequency, and ProSe configuration.

Case 3: Multiple Synchronization Sources of Same and Differing Types

Finally, in the most complex case a UE may receive more than one synchronization source for each of the three types identified:

- A UE in network coverage establishes a serving eNB. By standard a UE may encounter locations where it may be able to receive synchronization signals from eNB that are not synchronized. However, these events are anticipated to be the exception. Current LTE systems use synchronized eNB and usually to a basis standard. For example, GPS is directly traceable to a single standard. Small cells or temporary cells in indoor environments could be examples of potentially unsynchronized cells. An UE operating in such an environment simply roams or performs handover between cells. A ProSe UE is expected to use the timing of the current serving site. Therefore, ProSe essentially slaves its timing to its serving site and serving eNB changes may reset this timing when eNB are not synchronized. ProSe communication between devices that may be served by separate and unsynchronized eNB depend upon transmission of SLSS to allow the receiving ProSe UE to process the PC5 signal. From a user perspective serving cell changes with unsynchronized eNB are infrequent and expected to have little effect on user experience.
- A UE receiving SLSS based on network synchronization – SLSS based on network synchronization occurs when a UE receives SLSS that is transmitted by a ProSe UE that is in network coverage. Like the prior synchronization type the transmitted SLSS is slaved to the serving eNB and is therefore subject to timing changes associated with serving eNB changes. In contrast to the prior case, the ProSe UE must track each SLSS signal that it can differentiate. As each identifiable SLSS may represent a set of devices using the applicable SLSS as the basis for

[18] In this context concurrent decoding includes all primary synchronization signals that are currently active within a UE. Due to signal shadowing and fading all primary synchronization signals may not be decoded each time they are available. The UE is expected to maintain a list of active SLSS or network sources that persist across missed detections, but that are removed after some timeout period with no detections.

their communications. A UE not tracking a SLSS cannot communicate with the applicable UE set. Like the prior synchronization type, transitions between SLSS based on network timing that are unsynchronized are expected to be unusual events. Potential effects on user experience may be possible for this case due to propagation of delays. In this instance, the UE transmitting SLSS has an eNB change and accepts new timing. The UE must then update its SLSS timing and this new time basis must be recognized and accepted by the set of UE using this basis. The timing change may also have a cascading effect to other sets of UE that are using the third type of synchronization.

- A UE receiving SLSS based on an SLSS beacon that does not declare synchronization to a network. For this third type of synchronization the basis of synchronization is not declared and may be indirectly based on network timing through a chain of synchronization sources, may be based on an absolute time reference like GPS either directly or through a synchronization chain, or may be asynchronous. Since each synchronization source can be anticipated to serve a set of UE, receiving UE need to maintain multiple synchronization sources to ensure communication with devices in communication range.

5.1.5 SLSS Processing

Because the PSSS does not carry a device unique identifier its reception does not provide any identity information. In fact, a UE may receive multiple PSSS that are a combination of both root sequences, different center frequencies, and separate timing. Under certain conditions it may not be possible to separately track PSSS that are aligned closely in time or that precess through each other's time references.

A summary of common PSSS reception cases is shown in Figure 14. Use 0 is ProSe operation using the network as the synchronization source. For this case synchronization is simply based on the local network timing. ProSe devices relying on PSS will have common timing and use SIB information for operations.

Use 1 is operation with PSSS from a network based SLSS. Like the prior case the ProSe device tracks a single synchronization source that has a network basis. All timing is based on network time.

Case 2 is for single PSSS reception from a SLSS without direct network synchronization. Therefore, timing may be based on a synchronization chain from a network source, may be based on a separate absolute reference like GPS, or may be completely asynchronous. For reception of a single synchronization source there is little expected difference in performance or processing. For asynchronous sources, new timing may need to be acquired, but this would likely involve multiple received sources involving one or more of the cases below.

When ProSe operation includes reception of more than one synchronization source multiple timings and synchronization configurations may need to be tracked.

Case 3 receives network-based PSS and PSSS. In this case the PSSS may be directly synchronized with the network or may not be. Consequently, the UE in general needs to maintain two synchronization sources and provide communication services for both. The UE should include logic to recognize and combine related sources to reduce processing requirements.

Case 4 supports instances where a UE receives two SLSS one of each type: direct network-based and non-direct network based. The UE can track both SLSS independently provided their relative signal strengths both reside within the dynamic range of the receiver.

Use #	Use Case	Active SLSS	Root Sequence	SL-ID	Dynamic Range	Comment
0	Network sync	0	NA	NA		
1	Network based SS	1	25	{0:167}	*	
2	SS: Not directly network based	1	37	{168:355}	*	
3	Network sync & SLSS	1	25 or 37	{0:355}		
4	Both SLSS	2	25 and 37	Two IDs		
5	Multiple network based SS	2	25	Two from: {0:167}		
6	Multiple Not network based SS	2	37	Two from: {168:335}		
7	Mix of SS	3	25 and 37	Two from: {0:167}		
8	Mix of SS	3	25 and 37	Two from: {168:335}		

Figure 14, Synchronization use cases

Cases 5 & 6 are for two concurrent PSSS which use the same base index. For PSSS with enough spacing in time the UE can resolve and recognize both synchronization signals. For closely spaced PSSS signals it may not be possible to separately resolve. However, the UE would search for SSSS and decode PSBCH to determine if separate synchronization signals/ BCH exist. Specific processing is implementation dependent, but separate SSSS or BCH configuration decodes would in general be tracked as separate synchronization sources, while the same configuration would be combined as a single source. If the same configuration exists with large time dispersal it may be necessary to handle it as two synchronization sources.

Cases 7& 8 recognize that a mix of synchronization sources may exist and that tracking of multiple sources is necessary to ensure that communication is missed simply because it used an untracked synchronization source.

While the PSSS only has two root sequences the SSSS has 336. Half are dedicated to direct network synchronized sources and the other half to non-direct synchronized sources. This allows for a significant discrimination of synchronization sources. The standards do not prescribe how SL-ID should be allocated. However, a few rules can be suggested:

- Unique SL-IDs should be assigned for different BCH configurations within a potential communication zone.

- SL-IDs may be assigned to provide additional information about the basis of synchronization. By example a synchronization source might use GPS. Prioritizing this source above an asynchronous source would be desirable.
- More assigned SL-IDs increases SLSS processing burden and are likely to affect battery life. It may be desirable to limit the number of SL-ID that may be incident on a UE.
- Using SL-ID to segregate ProSe devices can be counterproductive to reliable communications. Instead segregation should occur at higher layers based on unicast and group identifiers.
- A UE operating off network without any available synchronization sources may pick an SL-ID randomly from a pool of available SL-IDs[19] that is mutually exclusive to any SL-IDs it may already know are assigned.
- A UE should support a mechanism to minimize the number of separate synchronization sources by bringing adaptable sources into alignment. Synchronization sources with a clear basis would not be considered adaptable and would include network based and GPS based sources. Other synchronization sources could be adapted overtime into synchronization. Methods to adapt synchronization sources are discussed in [[20]].

Tracking of SLSS is limited by the signal quality of each SLSS available to a ProSe receiver. Independent fading conditions can be presumed; by design synchronization sources are geographically dispersed. Total signal loss between a transmitter and receiver pair is frequently modeled as a slowly-time varying component associated with the distance and fixed obstructions along the communication path and a time varying component associated with multipath and associated fading processes. Due to the time varying component different SLSS may be received during each PSCCH period. SLSS /BCH signal are heavily coded signals and therefore can be decoded at SINR's below 0 dB. Consequently, some SLSS with enough SINR may be decoded in a PSCCH period may be decoded, while weaker SLSS may only be decoded some of the time. Tracking of sources is dependent on the received signal quality.

{! RECOMMENDED CAPABILITY – The next generation direct communication solution should maintain a long-term estimate of its frequency calibration that prioritizes sources.}

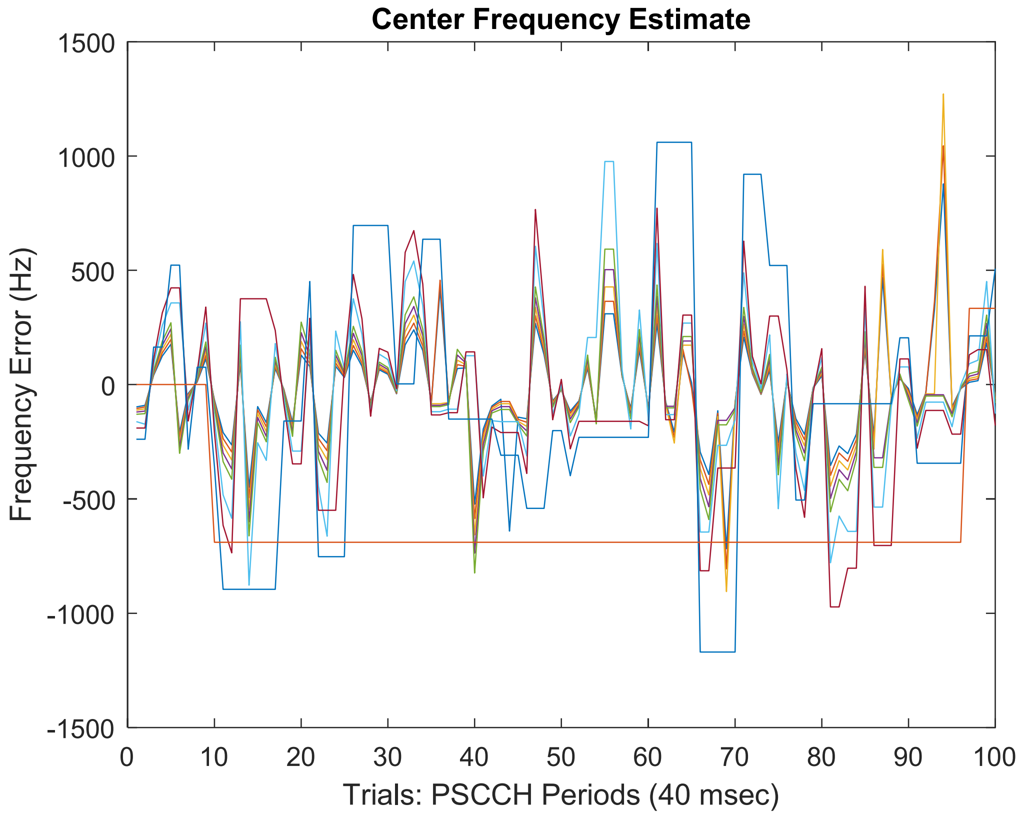
{! RECOMMENDED CAPABILITY – The next generation direct communication solution should maintain separate short-term estimates for each synchronization source it decodes.}

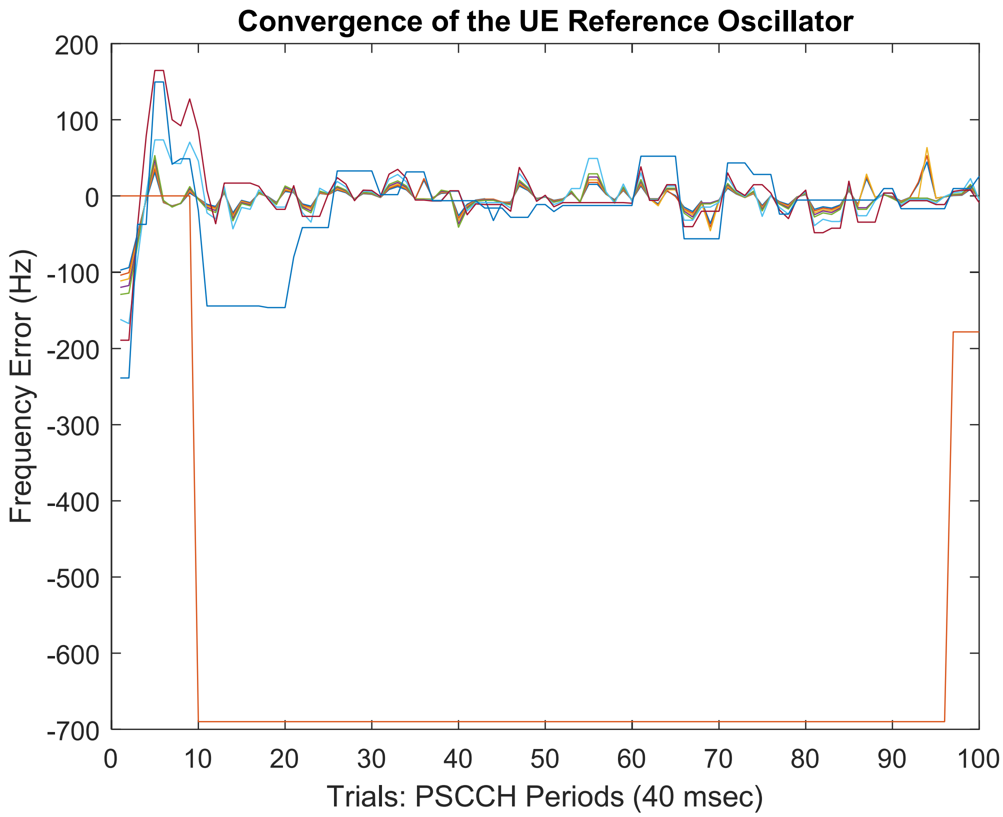
{! RECOMMENDED CAPABILITY – The next generation direct communication solution should provide a mechanism to update the long-term estimate from short term estimates that is based on a community

[19] The available pool size can also be one or equivalent to already assigned.

[20] Konstantinos Manolakis, Wen Xu, "Time Synchronization for Multi-Link D2D/V2X Communication," in IEEE 84th Vehicular Technology Conference, 2016.

estimate that weights synchronization sources according to their priority and estimated quality.}





Asdjfkl;

6. Addendum – Description of Sidelink Operations

Cell phone radio transport is either network based between an eNB and device or direct transport between devices. In addition, devices with relay capability may act as bridges between network and direct communications or direct to direct communication providing coverage extension.

Direct communication in LTE uses the Sidelink for communication between devices and is defined by the PC5 interface. The radio interface for Sidelink consists of 3 layers that include the physical layer (PHY), the medium access control (MAC), and Radio Resource Control (RRC). Detailed descriptions of these layers are provided in 3GPP 36.201 and its reference documents. This description is meant to highlight certain aspects of the Sidelink services applicable to this research program.

6.1 PHY Layer

The Sidelink PHY consists of several physical channels that support the radio interface and transfer information across the radio interface including:

PSBCH (Physical Sidelink Broadcast Channel) – This channel is transmitted with the SLSS (Sidelink Synchronization Signals) and includes basic information about the transmission format.

PSCCH (Physical Sidelink Control Channel) – This channel precedes the shared channel and defines transmission allocations that are used by the shared channel.

PSDCH (Physical Sidelink Discovery Channel) – This channel allows ProSe devices in proximity to discovery each other.

PSSCH (Physical Sidelink Shared Channel) – This channel provides the actual transport of data over the air interface.

The Sidelink PHY also includes physical signals that support synchronization and demodulation. These include:

PSSS (Primary Sidelink Synchronization Signal) – This signal is for initial synchronization of a SLSS receiving device

SSSS (Secondary Sidelink Synchronization Signal) – This signal may also be used for synchronization, but also includes certain critical information required for processing other channels.

PDRS (Demodulation Reference Signal) – This signal consists of known symbols spread throughout the time and frequency space of the physical signal to enable efficient channel estimation and equalization.

6.1.1 Synchronization

For Sidelink operation, time and frequency synchronization must be established between UE. Several different scenarios may exist depending upon RF conditions and the availability of Sidelink synchronization signals. ProSe supports the following synchronization sources.

In network – For UE within network coverage Sidelink communication is synchronized to the network. UE sharing a common serving eNB or served by synchronized eNB acquire synchronization to Sidelink directly from network timing.

Async. Networks – UE within network coverage can establish Sidelink communications between UE that may be served by separate eNB that may not be synchronized. In this case, Sidelink communications must support offset timing. UE frequency synchronization may still benefit from eNB high stability references.

Network Directed Synchronization Sources – The network can direct ProSe capable UE to act as Sidelink synchronization sources.

Fringe Network Coverage UE – Devices supporting Sidelink that do not have a network RSRP above a provisioned threshold and that also do not have a Sidelink RSRP above a separately provisioned threshold may act as Sidelink synchronization sources. This synchronization source uses network timing it obtains from its fringe coverage to establish its synchronization. It then uses this synchronization for subsequent direct transmissions. It will also employ this synchronization if it is provisioned or directed to become a synchronization beacon.

Off Network UE – Public safety devices supporting Sidelink that have no synchronization with a network, first attempt to find other synchronization sources. These may include other direct mode devices that either transmit a message which always include synchronization information or that transmit a synchronization beacon. The device may use any synchronization signals that it receives as a basis for its own transmission timing. However, reliable reception cannot rely on a single synchronization for reception. Devices may be RF isolated and may not receive a local synchronization beacon even when many nearby devices do. This device may then transmit asynchronously to the local synchronization beacon and is only heard by devices if they search for direct signals that may have arbitrary timing.

Sidelink receivers prioritize synchronization sources according to Table 7.

Sidelink receivers can maintain multiple synchronizations to support communication with Sidelink transmitters. The number of asynchronous sources varies with the scenario.

Table 7, Synchronization Sources

Scenario	Number of Synchronization Sources
Asynchronous eNB; In network device	In a regular tessellation of eNB, the handover region is typically characterized by 3 eNB's with similar strength signals. In principal each of these eNB's may have their own timing. While its true that fixed infrastructure is generally synchronized, synchronization may not be the case during public safety response when: 1) mobile eNB are brought in to increase capacity for an incident 2) when a disaster has knocked out high capacity backhaul links or 3) when mobile eNB are located within structures or geographic canyons. Therefore, a LTE-direct device may need to deal operate in an environment with at least 3 asynchronous eNB's.
In network Sidelink beacon	An out of network (PS) device receives Sidelink beacons that are synchronized to an eNB.
Out of network beacons (PS)	An out of network (PS) device receives several synchronization beacons that are not directly based on an eNB. In a worst-case scenario, UE transmitting Sidelink beacons are radially dispersed from the target UE. Each beacon is far enough from the others to prevent synchronization via 3GPP standard behavior. E.g. Without topological obstructions, each could be equally distant from the target and spaced radially by slightly more than 1 radian. which would ensure the distance between beacons was greater than the distance to the target UE. In principal, up to 6 synchronization sources would then be possible. Obstructions may also prevent synchronization sources from hearing each other.

The 3GPP standard defines a prioritization of synchronization sources and a device acting as a beacon may dynamically update whether the criteria to be a beacon is still valid. However, a beacon may not be aware of devices it is serving. Therefore, removing synchronization sources must be performed carefully.

One method to reduce the number of asynchronous synchronization sources in overlapping areas is to shift synchronization sources toward a weighted average of the sources that can be detected. The idea is to bring disparate time sources to a smaller number of references.

Unlike network unicast communications that adjust their UE transmission timing to compensate for airlink propagation, ProSe does not adjust its transmission timing. Therefore, the CP must be long enough to compensate for potential time skew between devices times. Scenarios

1. Common SLSS

2. Separate SLSS
3. Async networks
4. Sync networks

Recommended Requirement: GNSS should be added to the priority list of synchronization sources for ProSe.

Recommended Requirement: The PSSS signal should identify synchronization sources that are GNSS based.

Recommended Requirement: The 3GPP standard should define the time relationship between UTC time and the beginning of a PSCCH frame.

Recommended Requirement: The CP duration used in ProSe should exceed the worst-case propagation delay that may be expected in target PS scenarios.

7. Addendum – Direct Communications Requirements

This is an excerpt from the NPSTC Public Safety Communications Report, Public Safety Broadband Push-to-Talk over Long Term Evolution Requirements 7/18/2013. It provides requirements for direct communications.

Public safety communications systems are designed and built to enable first responders to communicate in the direst of circumstances. This includes instances where the public safety radio system they are operating on has had its infrastructure damaged or has completely lost the ability to function. In such circumstances, it is paramount that first responders retain voice communications capability directly, from radio to radio, without depending upon any infrastructure. This capability is possible due to a commonality that is planned for and included (common agency-based channels, common interoperability channels, etc.) in each public safety radio. While the NPSBN will be a primary, reliable transport of public safety voice and data, there are many situations where voice and data communications will be required in areas where the NPSBN is not available. NPSBN Users (NPSBN-U) may be outside of the range of the fixed network, such as first responders in a rural area assisting in a response to a plane crash or police officers inside a residence responding to a domestic issue. Off-network voice communications must be immediately accessible to users in the absence of the NPSBN. This includes areas and locations where the ability to access nonterrestrial communications can be impaired such as within building and other enclosed areas where non-terrestrial communications may not be available. Additionally, there may be times when users may wish to communicate off-network. Today, firefighters often join a local communications network, which does not leverage the fixed network, but rather, relies on either direct communications between the user devices or communications via a local repeater on-scene. Firefighters can voluntarily leave the fixed network either due to the unpredictable coverage of the fixed network, or if the coverage of direct communications or the local repeater is well known, based on experience. There will be occasions where a user may be within network coverage and will need to communicate with users who are on the network and off-network, such as an Incident Commander (IC) supporting fire response activities. These users must be able to communicate to users on the fixed network, such as dispatch, as well as the local users who are off-network or when it is desirable to provide voice, data and video connections between users without connection to the network even if within network coverage. A relay function is critical for off-network communications when NPSBN coverage is not sufficient to support the public safety mission. In the case of firefighters who are responding to a wildfire while outside of the coverage of the fixed network, if one user becomes encircled by the wildfire and is beyond the range of the IC, but within the range of another device that can act as a relay, the endangered firefighter can still update his status to the IC. A UE device operating on the NPSBN SHALL be capable of relaying PTT traffic between a UE device operating off the network and a UE Device operating on the network. 7.1 Off-Network Operational Communications In today's public safety environment, direct voice capability utilizes either mobile or portable radios with varying transmit values that operate in multiple frequency bands, providing a variety of range capabilities for users operating in the direct mode. Different frequency bands, by their nature, have varying range capabilities and that applies to operations in the direct mode. The transmit power, use of mobile or portable radios and the frequency band in use are all major factors in determining the distance over which two users can communicate in the direct mode. NPSTC Recommendations for PTT over LTE Requirements 31 PTT Off-Network Communications Requirements Public Safety Broadband The ability for NPSBN subscribers to operate in a peer-to-peer mode will enhance range possibilities between units and offer bandwidth extension between devices within urban areas. Direct mode communications could also offer the ability to enhance in-building coverage in the nation's cities. Non-terrestrial communications should not be considered an alternative to off-network (direct mode) voice capabilities. Non-terrestrial communications may not offer public safety users the same capability or accessibility as off-network, direct mode capabilities. The following are requirements for off-network operations.

Table 8, PTT Off-Network Communications Operational Requirements,

#	Requirement
1	Off-network PTT Communications SHALL not cause interference to on-network operations and on-network operations SHALL not cause interference to off-network operations.
2	On-network operations SHOULD not cause interference to off-network PTT Communications
3	Off-network PTT Communications SHALL minimize interference to other off-network devices.
4	Public Safety Users SHALL have off-network PTT Communications, as necessary and authorized, in the complete absence of any fixed infrastructure.
5	Off-network PTT Communications SHALL allow a minimum number of (N) simultaneous fffnetwork PTT Communication transmissions.
6	Off-network PTT Communications SHALL only be available for authorized users.
7	The PTT Service SHALL provide a notification to a user when approaching the edge of the network.[21]

7.2 Off-Network PTT Communications Status Following are requirements for the off-network communications status of users.

Table 9,PTT Status Requirements of NPSBN User Off-Network Communications

#	Requirement
1	A UE SHALL be capable of switching to an off-network PTT Communications mode when detecting an off-network condition.
2	The PTT Service SHALL allow an authorized user to move PTT Groups off network for use with off-network PTT Communications.
3	An authorized user SHALL be capable of switching to an off-network PTT Communications mode.
4	Off-network PTT Communications SHALL provide a range similar to what is offered by current LMR solutions at an outdoor incident scene.[22]
5	Off-network PTT Communications SHALL provide a range similar to what is offered by current LMR solutions between users within a building and users outside of the building.[23]

[21] Could include audible, visual, or vibration notification.

[22] There are many ways to provide this capability, including but not limited to higher power UEs or portable infrastructure.

[23] The users within the building may be on different levels/floor and at varying distances within the building.

6	Off-network PTT Communications SHALL support a number of (N) PTT Groups as authorized by the agencies System Administrator.[24]

7.3 Off-Network UE Functionality On-network communications is usually the preferred communications path. However, because fixed network coverage cannot be provided everywhere, it is beneficial for devices to be able to relay communications from off-network devices to the fixed network, when possible. An example of the benefit of this case, is when a user who enters an emergency condition is out of the fixed network coverage, but is within the coverage of another device that is in network coverage. By relaying the emergency state of the off-network user, critical information is passed to the network to protect the life of the user. The capability of NPSBN users to be able to communicate simultaneously with the NPSBN on-network and users who are off-network may also be required during mission critical incidents. Typically, users operating off-network will want to discover other users, and be discovered by other users on the scene. Sometimes, users will not want to be discovered, such as undercover agents in the area. Other times, users may not want to participate in off-network communications at all. Because of this, the ability to configure a device to discover other users, to be discoverable by other users, and to permit or restrict off-network communications, must be supported. Following are UE requirements for off-network communications.

Table 10, Off-Network Communications UE Functionality Requirements

#	Requirement
1	A UE SHALL be capable of off-network PTT Communications and on-network PTT at the same time.
2	Off-network PTT Communications SHALL provide a mechanism to dynamically create PTT Groups.
3	Off-network PTT Communications SHALL provide a mechanism for a UE to monitor what PTT Groups are active.
4	Off-network PTT Communications SHALL provide a mechanism for a UE to relay off-network PTT Group transmissions from an on-network UE to an off-network UE.
5	Off-network PTT Communications SHALL provide a mechanism for a UE to relay off-network PTT Group transmissions between off-network UEs.
6	A UE SHALL be capable of transmitting its location, if known, to other UEs when operating offnetwork.
7	A UE SHALL be capable of utilizing off-network PTT communications while still connected to the NPSBN and access required services.
8	A UE SHALL be capable of being connected to the NPSBN and utilizing required network services while operating off-network PTT communications.

[24] Breaking with the qualitative nature of this document, the minimum number of PTT Groups that must be supported is a minimum of 20.

8. Innovation Concepts

8.1 Channel Aware CODEC

The EVS channel aware CODEC can maintain acceptable MOS results with a missing frame rate of 8%. This error rate is most obviously allocated to the receiver performance. However, it may also be proportioned to the transmitter not generating a frame. Can un-transmitted frames be used to greater advantage in system performance than allocating all frame loss to the receiver?

8.2 Macro-diversity Transmissions

Harris has identified a potential extension to ProSe that provides clear advantages to coverage when multiple ProSe devices are available and mutually within coverage. The following sections describe the techniques and provides simulation results demonstrating its capabilities.

8.2.1 Description

8.2.1.1 Background

ProSe supports both broadcast and unicast communication capabilities, but broadcast operation is particularly important to first responders because they commonly communicate in groups. Broadcast allows communications to be delivered simultaneously to all members of the group and thereby by provides rapid communications that facilitate quick support and response. It also provides more efficient use of RF resources because a single message is decoded by all interested users, rather than individual messages for each user. Simulation performed during development of the ProSe standard identified that communications may encounter system self-interference that significantly limits range. This interference results from other devices transmitting in the same coverage proximity as a receiving device. These devices may be attached to the network or be operating off- network in public safety ProSe mode. While network devices may interfere with ProSe operations, off network device transmissions cause more interference.

Network devices transmit according to scheduling from a serving eNB which dictates RF resources that are configured by design to provide isolation from resources used by ProSe devices. Furthermore, network device transmission power is tightly controlled by the eNB. It adjusts device power to the minimum required for efficient data transmission. Tight power control is possible because this network uplink traffic is unicast with a low latency HARQ process. The eNB calculates signal quality metrics that measure the performance of the device uplink. It then completes a feedback loop to the device to ensure that it operates at minimum transmission power for reliable data transport. Accordingly, devices can transmit at 23 dBm, but most commonly operate at much lower power.

In contrast to network devices, PS mode ProSe devices that are providing broadcast communication services cannot take advantage of the tight feedback system used in network UL transmissions. First, public safety group communication reliability should be maximized to the most remote device in the group. However, RF losses to the most remote user are generally unavailable and rapidly change. Accordingly, the transmission must be performed at full power. In general, talkgroup members are each subject to separate and independent communication limitations that are a function of the desired signal quality as well as system self-interference. Figure xxx illustrates some simplified examples of a single talk group that spans:

- Network coverage

- Network accessible devices via network extension relay
- Adhoc ProSe – segregated talkgroup subset of the same talk group
- Adhoc coverage segregated talkgroup subset that includes a network extension-relay
- Isolated devices – devices out of range of other networks and devices

The 3GPP standards activities did not generate a solution to this problem and therefore the most effective way to provide reliable transmission to a group is full power transmission.

{REQUIREMENT! – Broadcast ProSe communications should operate at maximum power.

In addition to maximum transmission power, 3GPP decided to implement repeated transmissions to improve the reliability of receiving a message. ProSe self-interference is a complex function of interfering transmission activity in range of the victim receiver. The imposed interference depends on the incident power of the transmission intercepted by the receiver as well as the timing and frequency relationship between the transmission energy and the desired receiver resource elements. By simple example a receiver may encounter significant interference in the transport block, but very little interference 1 msec. later in the next transport block. Thus, multiple transmissions can substantially improve the likelihood for receiving a message. The standard decided that PSCCH messages that are relatively short and fixed in length would be sent twice. PSSCH messages which depend upon the MCS selected and could be much larger would be sent 4 times. During periods of low interference (low loading of RF resources available to ProSe communications) this redundancy properly processed at the receiver improves link margin, thereby extending coverage. During high interference some transmissions may be blocked, and redundancy makes it far more likely that the receiver will be able to decode the message by receiving some fraction of the redundant messages. The interference in effect reduces redundancy and therefore coverage is affected by loading. At sufficiently high loading the redundancy is counter-productive, and the capacity of the channel falls off. Judicious use of priority and congestion control measures implemented by the transmitters can prevent an inefficient channel.

8.2.1.2 Macro-diversity Transmissions

Macro-diversity ProSe transmission is a mechanism to improve the range and reliability of public safety ProSe communications. The principal concept is that retransmissions, already part of the ProSe protocol, can be reinforced by other ProSe devices. The likelihood that a ProSe receiver will be able to decode an initial ProSe transmission decreases with increasing equivalent RF distance to the transmitter. Consequently, receiving devices near the transmitter are likely to decode a first transmission while devices further away are increasingly less likely to be initially successful. Macro-diversity ProSe transmission employs these initially successful receivers to transmit during the redundant portions of the original message. Specifically, a receiver that successfully decodes an initial transmission, captures the transport block and synchronously transmits with the initial transmitter in subsequent redundant transmissions.

Figure 15 illustrates how this form of macro-diversity works. In this example device A wants to communicate with the talkgroup that consists of all devices shown. However, its ability to do so is limited by obstacles and distance. Per ProSe standards it sends its transmission message 4 times. Devices B, C, and D that are within proximity to device A receive and decode the first transmission. They then synchronously repeat the message precisely echoing device A transmissions. This effectively removes the obstacle prevent communication with device E, while also extending range to devices F and G.

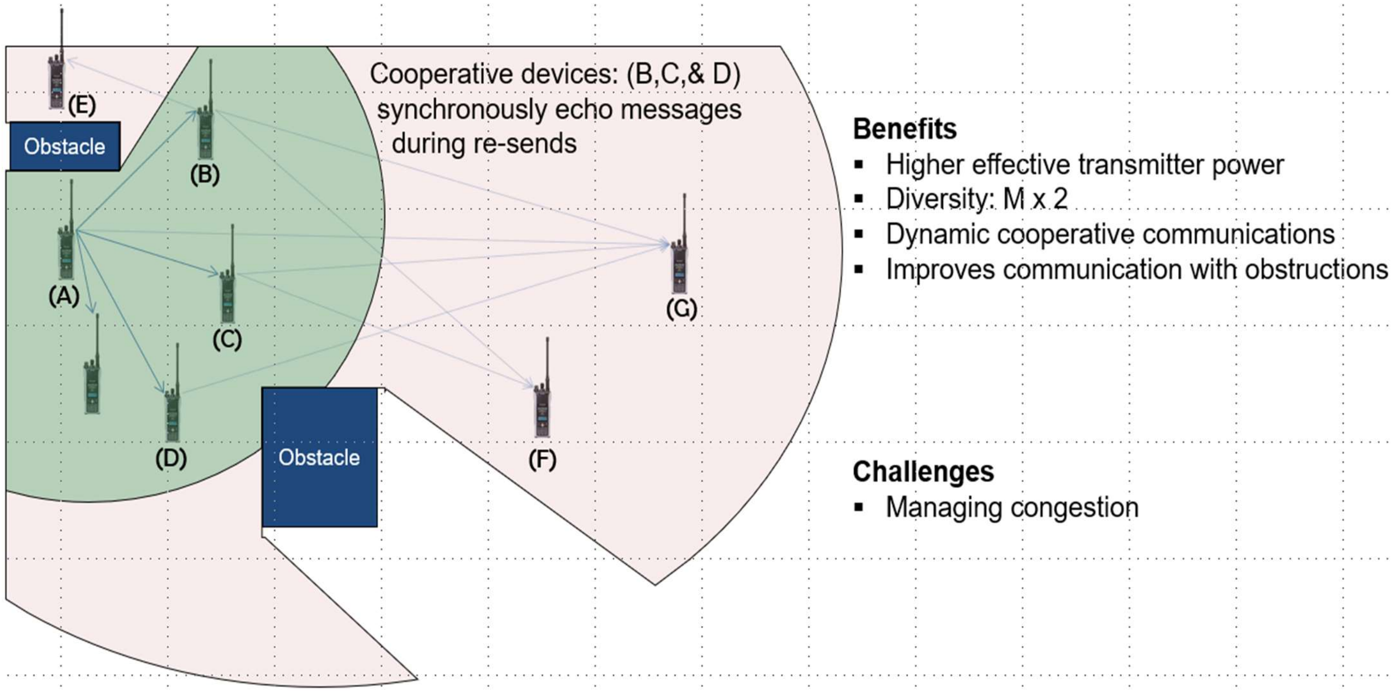


Figure 15, Macro-diversity

As illustrated in Figure 16, an originating device transmits and implicitly initiates support devices to mimic the first transmission on subsequent transmission periods. Potential support devices base whether they will support a transmission on several factors including:

- Their configuration that may define whether devices are enabled to support transmissions and under what conditions support is provided.
- Devices may also selectively support transmissions depending upon the priority.
- Finally, devices may use radio metrics like signal strength to decide whether a transmission should be supported.

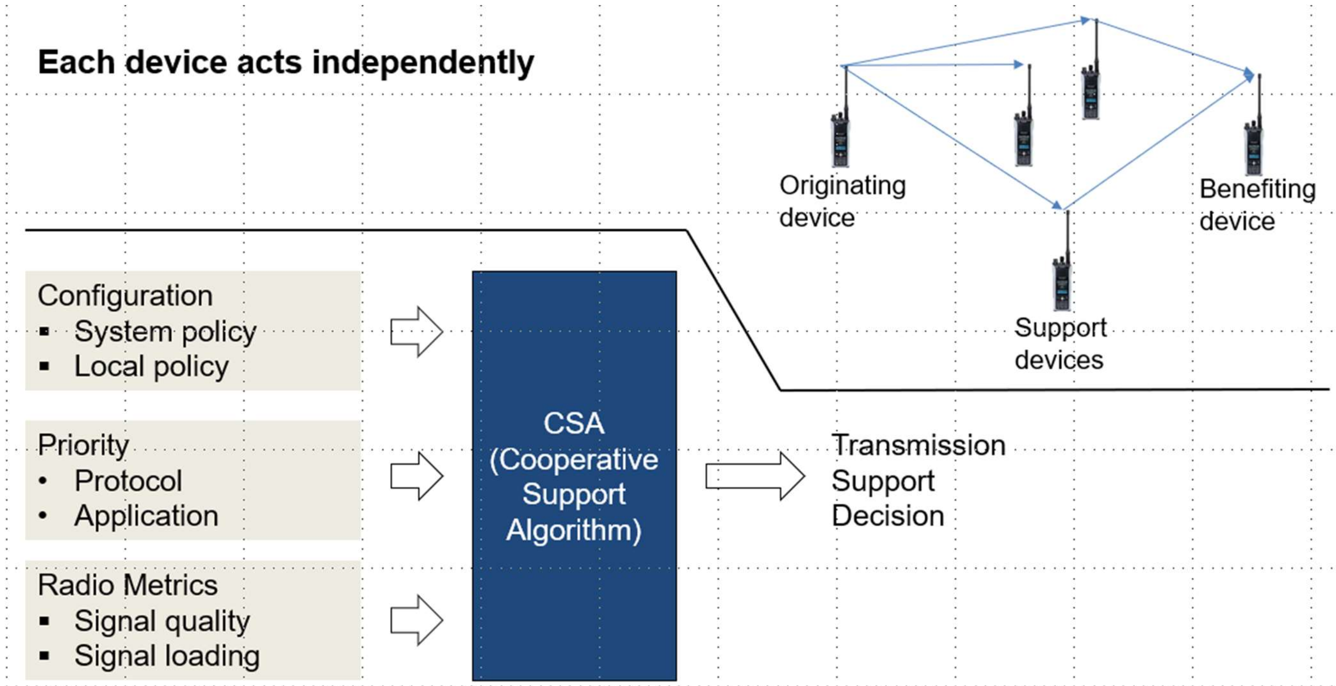


Figure 16, Macro-diversity approach

Macro-diversity offers multiple benefits from a coverage and reliability perspective.

- More efficient than a relay – coverage extension-relays and network extension-relays operate by receiving complete transport blocks including all redundancy. Following complete reception, the relay selects additional resources and completes another transmission including redundancy. Consequently, twice as many resource blocks are required for each message passing through a relay. Macro-diversity transmissions do not increase the number of resource blocks required for message delivery.
- Inherently adaptive to current RF conditions – Macro-diversity dynamically enlists other devices that can decode the initial transmission and are otherwise qualified to reinforce transmissions. As devices move around they move in and out of acting as reinforcing transmitters according to their ability to decode the initial transmission and other qualifying metrics.
- Reduces near/ far interference issues – Most intra-system interference in ProSe results from receivers operating close to a transmitting device that is a member of a different communications group or is independently transmitting unicast traffic. Blocked reception is a strong function of the ratio of the incident interfering transmitter power to the desired transmitter power. Macro-diversity lowers this ratio on average.
- Extends range – Macro-diversity extends range via higher transmission power, a richer diversity RF field, and by obviating RF obstacles. Each transmitter that operates during redundant periods adds to the average power of the transmission. Each transmitter also adds to the richness of the diversity field. Reinforcing devices will be far enough apart that their respective paths to the receiver are independent fading processes. It is therefore increasingly unlikely that multiple paths will simultaneously fade and prevent message transport. Finally, macro-diversity improves signal propagation around RF obstacles. RF signals have limited ability to

transmit around obstacles, however reinforcing transmitters may eliminate obstacles simply by their separate location.

- Improve communication reliability – The net effect of this richer diversity field, higher transmitter power, and location diversity is that group communications are more reliable. Multiple transmitters improve the likelihood that all members of a communication group receive a message.
- Extends priority and preemption paradigm – Finally, diversity transmission may be applied selectively to messages. Decoding success is required for reinforcing transmissions, but transmissions may also be qualified by: received power, signal quality, and loading metrics. In addition, diversity transmission may be qualified by priority fields contained within the control channel for each message. In a heavily loaded channel this ensures that messages with the highest priority are given privilege.

9. References to relevant 3GPP documents

9.1 Interference Cancellation

TR36.766 Study on interference cancellation receiver for LTE BS

TR36.859 Study on Multi-user Superposition Transmissions

TR36.884 MMSE-IRC receiver

TR36.891 Network Assisted Interference Cancellation

9.2 ProSe

TR36.843 Study on LTE ProSe

TR36.877 Study on ProSe User Equipment

9.3 V2X

TR36.785 V2X Radio Transmission

TR36.786 V2X Services

TR38.787 V2X New Bands

TR38.788 V2X Phase 2

TR36.885 Study on V2X

9.4 Voice Quality and Coding

TR26.952

TR26.989 MCPTT Media, codecs, and Multimedia Broadcast/ Multicast Service (MBMS) enhancements for MCPTT over LTE

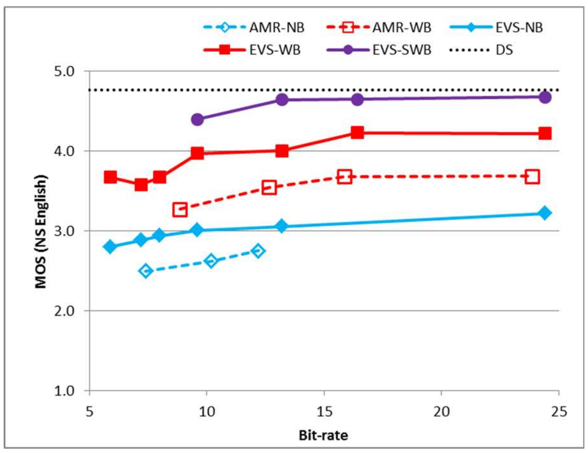
> TR26.989 provides a comprehensive comparison of voice codecs and their relative perceptual performance. In summary EVS was equivalent or outperformed AMR and AMR-WB vocoder under a battery of tests that included RF channel impairments as well as acoustic impairments defined by an NTIA report.[25] Evaluations were performed using models for LTE unicast operations, LTE broadcast operations, and LTE-direct (ProSe) with frame erasures that were randomly distributed and per the Delay and Error profiles from TS 26.114 using the EVS JBM.
>
> Despite the EVS performance advantage, AMR-WB was selected as the recommended mandatory due to its wide current adoption in existing networks, as well as uncertainty over the

[25] NTIA Report 15-520: "Speech Codec Intelligibility Testing in Support of Mission-Critical Voice Applications for LTE", S.D. Voran & A.A. Catellier September 2015.

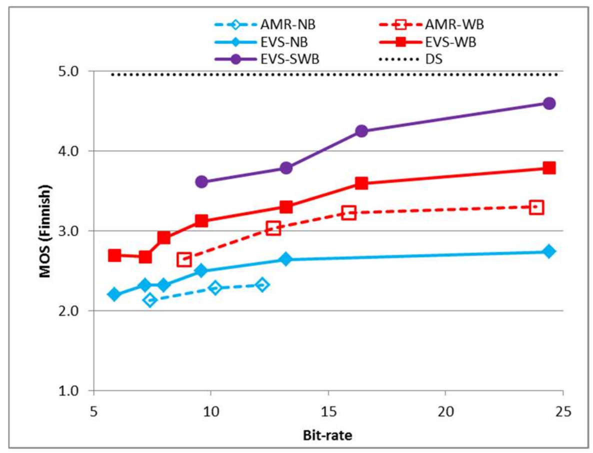
licensing costs of EVS. EVS-SWB was also recommended as an optional CODEC for MCPTT operations.

Table 11 illustrates the audio quality performance of the recommended CODECs in various acoustic environment scenarios. For comparison purposes the bit-rate for AMR-WB is 12.65 kbps and EVS-SWB is 13.2 kbps. Under clean audio conditions the AMR-WB achieves a MOS score of 3.5 while EVS-SWB achieves 4.7. Likewise, under the car noise condition AMR-WB has a MOS of 3.0 while EVS-SWB achieves 3.8. Finally, with music and mixed content AMR-WB achieves MOS of 2.7, while EVS-SWB maintains 3.7. The 3GPP document notes that acoustic noise suppression capabilities may reduce the audio quality differences in noisy environments.

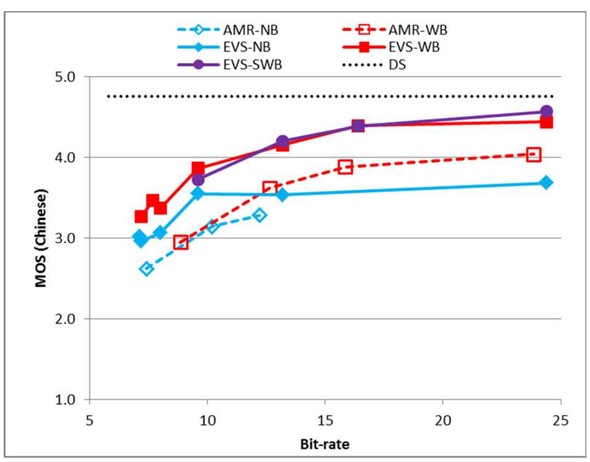
Table 11, MOS Scores for Selected CODECs



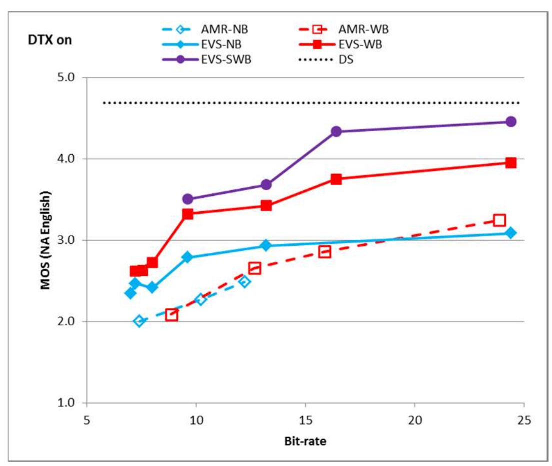
(a) Clean



(b) Car Noise



(c) Music & Mixed Content - Chinese



(d) Music & Mixed Content - US English

Table 12 illustrate the vocoder and transmitter mode combinations that were evaluated. The highlighted row shows the mandatory AMR-WB CODEC and forms the baseline of simulations to be used on this program. Additional simulations may be performed at the higher BLER allowed by the EVS CODEC.

Table 12, Coded voice cases for LTE-direct

Codec and mode	On time	Packet size	BLER target
AMR 12.2 kbps/AMR-WB 12.65 kbps	75%	44 Bytes	2%
EVS 13.2 kbps channel aware mode (Option 1)	72.5%	44 Bytes	8%
EVS 13.2 kbps channel aware mode (Option 2)	66.5%	44 Bytes	2%
EVS 13.2 kbps non channel aware mode (Option 1)	72.5%	44 Bytes	4%
EVS 13.2 kbps non channel aware mode (Option 2)	70.5%	44 Bytes	2%
EVS WB VBR 5.9 or 7.2 or 8 kbps	72.5%	31 Bytes	2%
NOTE 1: Option 1 is RX side BLER relaxation. Option 2 is TX side relaxation where 6% of the packets are dropped at the transmitter while keeping the same RX BLER target of 2% (net FER is 8%) for the channel aware mode. For non-channel aware mode, 2% of packets are dropped at the transmitter and RX BLER target is kept at 2% (net FER is 4%). NOTE 2: The EVS-VBR (variable bit-rate) mode combines bit-rates of 2.8 kbps, 7.2 kbps and 8 kbps to achieve an average bit rate of 5.9 kbps over active speech. For purpose of this simulation, 2.8 kbps and 7.2 kbps packets were zero padded and sent at the same payload size as 8 kbps, i.e. 31 Bytes.			

TR26.114 IP Multimedia Subsystem (IMS); Multimedia Telephony; Media Handling and Interaction

Includes the EVS JBM profiles.

9.5 NB-IoT

TR36.802 NB-IoT

TR36.888 Study on IoT

9.6 In-device Co-existence

TR36.818 In-device coexistence

9.7 Relays

TR36.836 LTE Mobile Relay

9.8 High Power UE

TR36.837 HP-UE

TR36.886 Study on B41 HPUE

9.9 Misc

TR36.824 LTE Coverage Enhancements

TR36.868 Study on Group Communications

TR36.898 Network Assistance for Network Synchronization