Circuit-switched fallback to 1x voice: Network architecture, options and performance

White Paper
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LTE growth and challenges

The 3GPP Long Term Evolution (LTE) high-speed, high-capacity data standard for mobile devices is firmly established as the global technology for 4G. Launched commercially in late 2009, current deployments and planning worldwide have expanded as shown in Figure 1. As an all-IP transport technology using packet switching (PS), LTE introduces challenges to satisfying established quality of service expectations for circuit-switched (CS) mobile telephony and SMS for LTE-capable smartphones, while being served on the LTE network.

The long-term solution to providing traditional circuit switched services is to support IMS based voice (VoLTE based on IR.92) and IMS based SMS. Operators migrating from CDMA2000-based 3G networks to LTE have two approaches to provide voice services before VoLTE is deployed: dual-radio solutions and single-radio solutions.

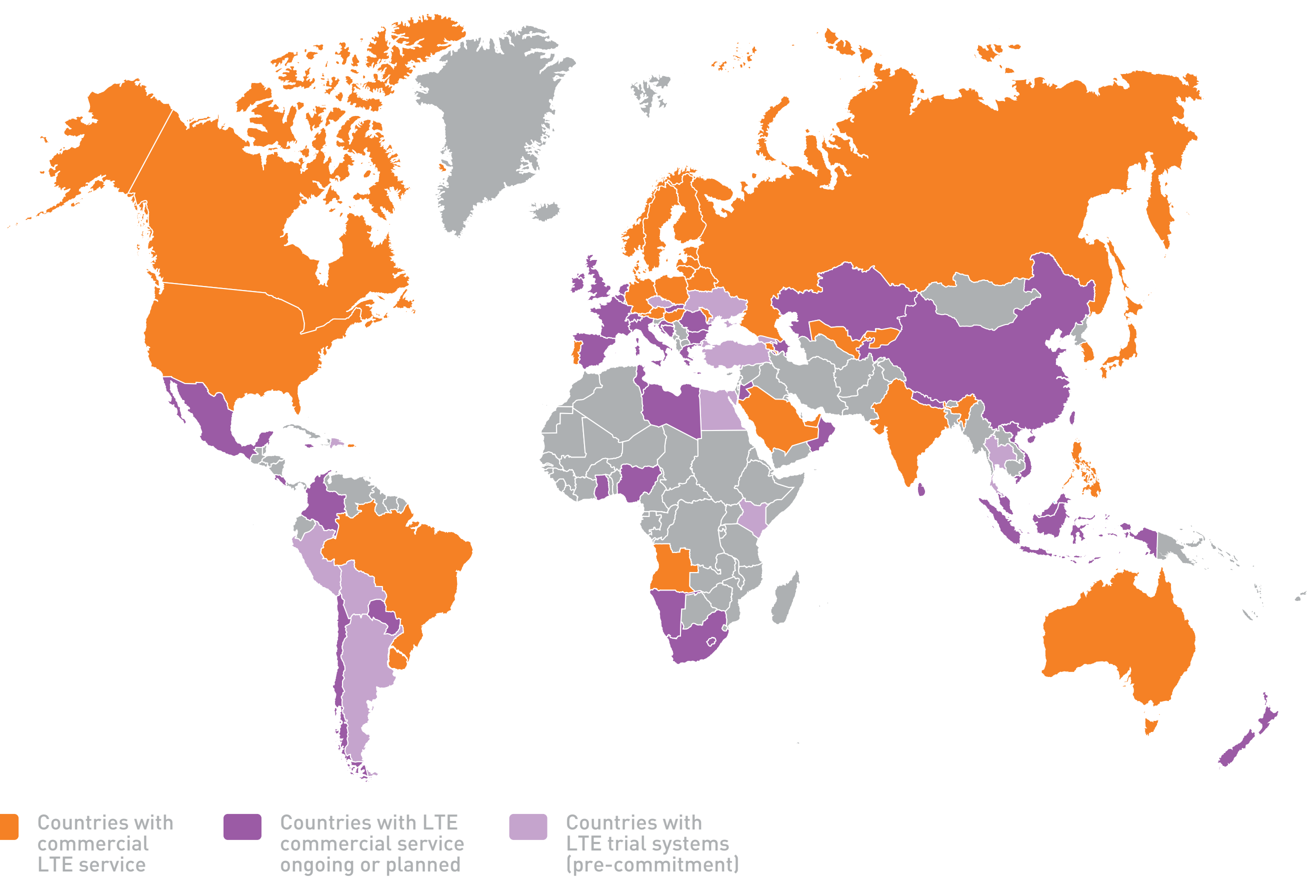
Dual radio solutions—also known as Simultaneous Voice-LTE (SV-LTE)—use two always-on radios (and supporting chipsets), one for packet switched LTE data and one for circuit switched telephony, and as a data fallback where LTE is not available. Dual radio solutions have emerged for LTE-CDMA2000 network interworking to meet two near-term operator needs:

- Accelerating time-to-market for initial LTE smartphones
- Reducing network investment by avoiding upgrades to the network that connects the LTE core network with the 1x core network
- Differentiating by being the first to support simultaneous voice and LTE data rates on LTE smartphones in advance of commercial availability of VoLTE

While dual radio SV-LTE provides a relatively simple network, its long term utility is limited by at least six complicating problems:

Figure 1

May 2012 LTE deployment and plans



- With two always-on radios, devices require more battery power and internal physical space, compromising battery life and device design aesthetics
- Two radios and their supporting chipsets increase device design and manufacturing cost, with no compensating gain in user benefits
- Frequency interference between radios may reduce effective range and useful bandwidth
- For roaming, each roaming partner's LTE and 1x band combinations must be tested for SV-LTE RF level compatibility, and the RF mitigation solutions needed for each unique combination may limit the number of networks the device can roam into
- Operator infrastructure is taxed with a double connectivity burden for each dual radio user device
- Dual radio solutions are not in the voice evolution road map, so development investments have limited longer term utility

Single radio solutions use one radio to handle both types of traffic, and use network signaling to determine when to switch from the PS network to the CS network. This 1x circuit switched fallback (1xCSFB) is based on 3GPP Technical Specification 23.272—*Circuit Switched Fallback in Evolved Packet System*, Stage 2—and is the focus of this paper. The main benefits of single radio solutions such as 1xCSFB are:

- Reduction in user device complexity, board area and power consumption, enabling smaller, thinner form factors that characterize today's leading high-tier smartphones
- Faster voice call setup times than native 1x and dual radio SV-LTE, especially for incoming calls
- Greater support for voice and SMS roaming on 1x/LTE multimode devices, utilizing established 1x voice/SMS roaming agreements, since it eliminates the need to test every LTE-1x band for SV-LTE RF level compatibility
- When 1xCSFB is supported in the network, a CDMA operator can support both single radio and dual radio inbound 1x/LTE roamers

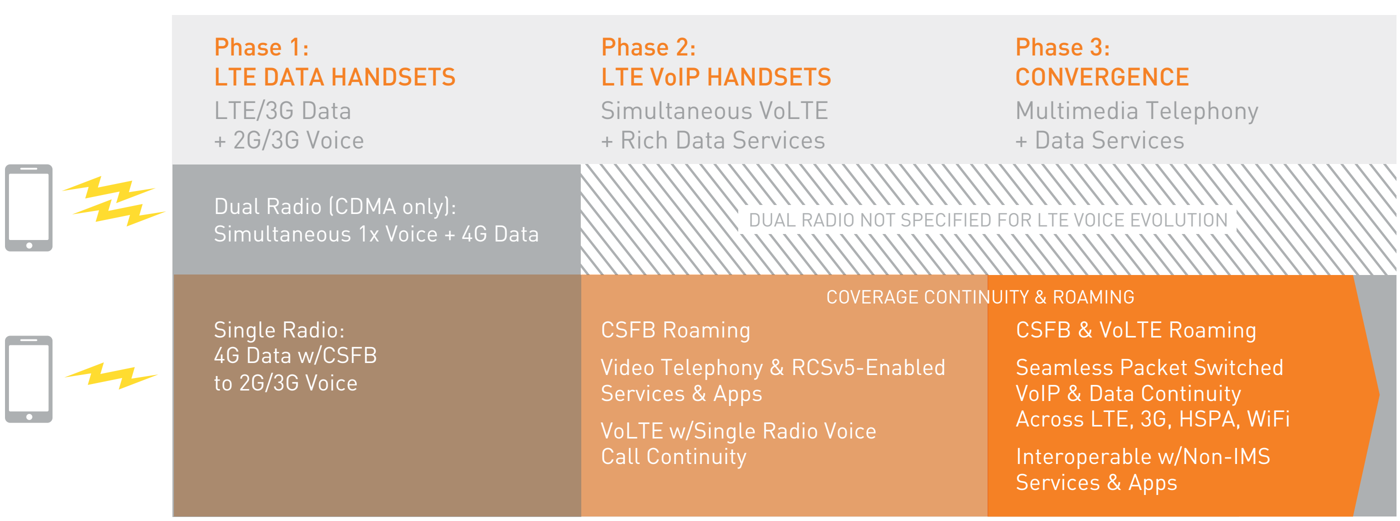
The 3 phases of LTE voice and communication services evolution

The handling of voice traffic on LTE handsets is evolving as the mobile industry infrastructure evolves toward higher—eventually ubiquitous—LTE availability. Central to the LTE smartphone value proposition is meeting today's high user experience expectations while evolving the entire communications experience, and by augmenting legacy voice with richer media services.

This voice evolution can be characterized into three major phases, summarized in Figure 2.

Figure 2

The 3 phases of LTE voice evolution



In the first phase, currently under way, all voice traffic is handled by legacy Circuit-Switched (CS) networks, while data traffic is handled by LTE Packet-Switched (PS) networks—when and where available—and by 2G/3G networks in non-LTE areas. Single radio solutions use 1xCSFB to switch between LTE and 1x access modes, while dual-radio solutions use SV-LTE for voice services on 1x, while also being camped on LTE. A more detailed comparison of the performance of 1xCSFB and SV-LTE devices is provided in the "Dual radios vs. single radios" section on page 10.

The second phase in LTE voice evolution introduces native VoIP over LTE (VoLTE) along with enhanced IP multimedia services such as video telephony, HD Voice and Rich Communication Suite (RCS) additions like instant messaging, video share and enhanced/shared address books. This phase also uses a single radio solution with Single Radio Voice Call Continuity (SRVCC) that seamlessly maintains voice calls as mobile users move from LTE to non-LTE coverage areas. 1xCSFB continues to be deployed during phase 2, to provide voice services for roamers and 1xCSFB-only devices.

1xRTT is the system with the highest voice capacity and quality, and 1x-Advanced enhancements extend these advantages across an even larger 1x installed base.

The third phase—all-IP networks significantly further in the future—converges the native power of IP to deliver enhanced capacity, value-added services (e.g., voice and video over IP and rich communication services) and interoperability across network access methods and operators (LTE, 3G/HSPA, WiFi and legacy telephony domains).

1xCSFB network architecture

The legacy 1x network and the LTE network co-exist in mixed networks, residing between the mobile customer's User Equipment (UE) and the common core network. An MME (Mobility Management Entity) serves users during LTE access, while an MSC (Mobile Switching Center) Server connected to the carrier's telephony network serves 1x users for voice services. To support CS Fallback signaling, SMS transfer and 1x network-based location services for LTE devices, the MME connects to the MSC Server through a 1x Circuit Switch Interworking Solution (1xCS IWS).

The architecture in Figure 3 shows a simplified view of the parallel LTE and 2G/3G networks.

As noted in Figure 4, the 1xCS IWS is an addition to legacy networks, while the MME and the Evolved Node B (eNodeB) are existing equipment that need upgrades to support e1xCSFB. The legacy MSC and the 1x Radio Transmission Technology Radio Access Network (1xRTT RAN) do not require modifications to support 1xCSFB. The interface (S102) between the IWS and the LTE MME enables the user's device to be both CS and PS registered while on the LTE access network. This interface also enables the delivery of CS pages via the LTE access, as well as delivering incoming and outgoing SMS, without having the device leave LTE.

Figure 3
1xCSFB network architecture

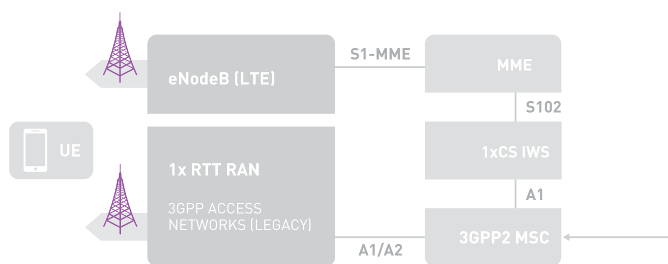
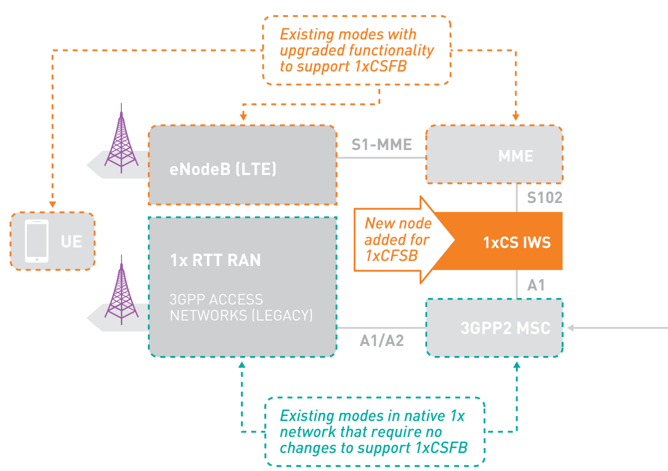


Figure 4
Equipment additions and upgrades



1xMSC registration via LTE

As shown in Figure 5, when a mobile device camps on LTE, it uses the presence of the parameters related to 1x registration in the System Information Block 8 (SIB-8) broadcast message to learn that the LTE network supports 1xCSFB with an S102 tunnel to the 1x network. The information in the SIB-8, together with additional information delivered to the device using Radio Resource Control (RRC) signaling, allow the UE to form a 1x Registration Message (RGM), encapsulated into a Generic Circuit Switched Notification Application (GCSNA) message. This GCSNA message is transparently carried by the eNodeB and the MME to the 1xCS IWS through the S102 tunnel. The 1xCS IWS extracts the RGM and updates the 1x MSC about the location of the UE using an A1-Location Update message. The MSC then knows how to reach the device when it receives a mobile terminated voice or SMS.

Incoming call setup

When the device receives a mobile terminating (incoming) CS voice call, the MSC delivers the page to the correct 1x IWS based on the prior registration performed by the device. The 1x IWS encapsulates the page message in a GCSNA message and sends it via the S102 tunnel to the LTE network. This gets delivered transparently to the UE, possibly preceded by an LTE page to bring the device to connected mode on LTE. (Figure 6)

The device responds to the 1x page with an extended service request (ESR) back to the network to request transition to 1x to receive the voice call. (Figure 7)

Figure 5

S102 registration with 1x MSC when camped on LTE

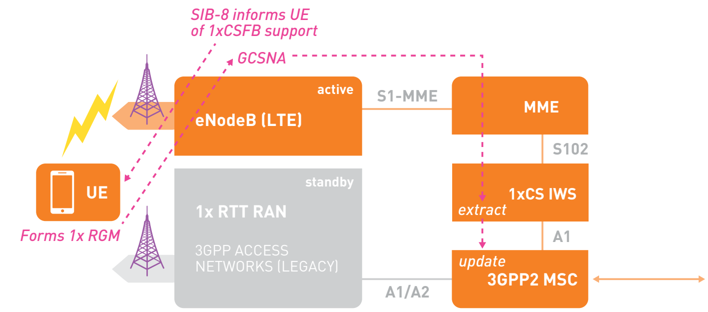


Figure 6

Incoming call page to device via LTE

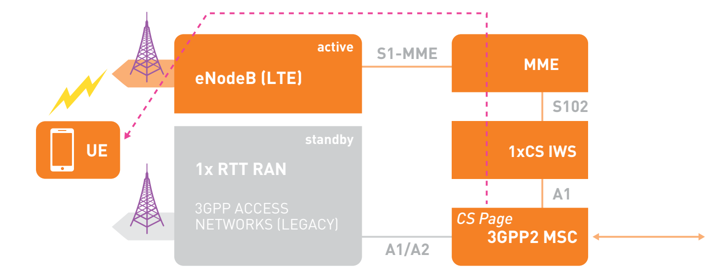
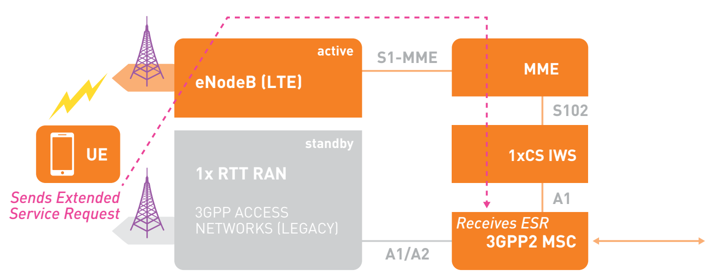


Figure 7

Extended service request response from device



The eNodeB, MME and 1x IWS interact to supply 1x traffic channel assignment. (Figure 8)

The device transitions to the 1x network to receive the call. (Figure 9)

Outgoing call setup

Mobile originating (outgoing) calls follow the same transition from LTE to 1x, except for the paging step, which is not needed.

When the device is on a 1x voice call, the PS data sessions are suspended until the voice call ends. Depending on the duration of the voice call, the data session can generally be resumed without loss in IP continuity as a result of the transition to 1x for a 1xCSFB call.

Return to LTE

When the voice call ends, the device attempts to return to LTE immediately by performing a scan of the LTE channels. (Figure 10)

Voice network acquisition

When the user's device is paged via LTE due to an incoming call, or when the user initiates an outgoing call, the device switches from LTE to 1x, as described above. Acquisition of the 1x network and setup of the call can employ one of two procedures: *redirection or handover.*

In the redirection-based 1xCSFB, introduced in 3GPP Release 8, only the target frequency is indicated to the device. The device is then allowed to pick the best cell on the indicated frequency, or may even try other frequencies or radio access technologies if no suitable cell can be found on the target frequency. Once a cell is selected, the device initiates normal call setup procedures. Inter-Radio Access Technology (IRAT) measurements of signal strength may optionally be used to determine the target frequency.

Mobile network operators raised concerns about the call setup delay with redirection based 1xCSFB in 3GPP Release 8. As a result, 3GPP release 9 introduced

Figure 8
eNodeB, MME & IWS supply 1x traffic channel assignment

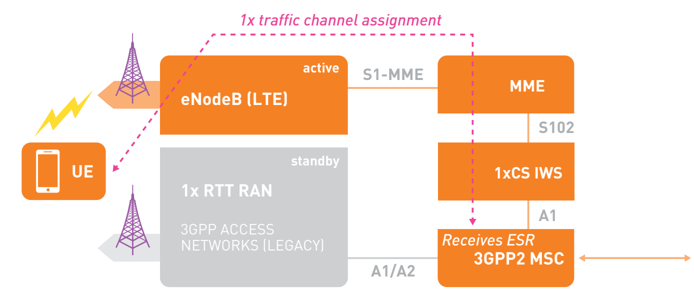


Figure 9
Device transition to 1x network to receive call

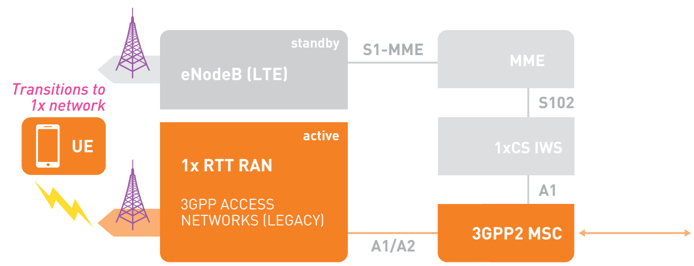
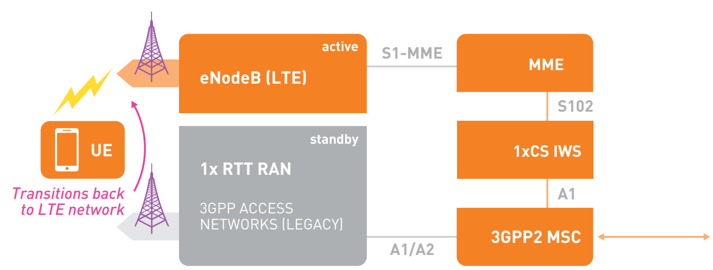


Figure 10
Device transition back to LTE network when call ends



enhanced 1xCSFB (e1xCSFB) using the handover procedure. Most operators deploying 1xCSFB to support voice on LTE smartphones are planning to use the newer e1xCSFB procedure. In this case, redirection-based 1xCSFB procedure will be used only under special conditions.

In the handover procedure, the target cell (or cells) is prepared in advance using the S102 tunnel to the 1xCS IWS, and the device can enter a pre-prepared cell directly in connected mode. IRAT measurements of signal strength measurements are required while on LTE in this procedure to make an informed handover decision prior to making the handover.

The e1xCSFB (handover) process

The LTE network learns about the device capabilities through the *UE Capability Transfer* RRC procedure. During this procedure, the device informs the network of its support of e1xCSFB and this information about the device is stored in the MME. (Figure 11)

The latest standard allows the device to provide different e1xCSFB capabilities based on whether it is operating on FDD-LTE or TDD-LTE. If desired, the device can be made to advertise that it supports handover-based e1xCSFB while on FDD-LTE but only supports redirection-based 1xCSFB while on TDD-LTE.

When the user originates a voice call or the device receives an incoming tunneled 1x voice page, the device performs the ESR to initiate 1xCSFB. Upon receiving the ESR, the MME informs the eNodeB that the device wants to perform a 1xCSFB procedure, and that the device supports e1xCSFB handover. (Figure 12)

In response, the eNodeB chooses to use the e1xCSFB handover procedure instead of redirection. In preparation for the handover, the eNodeB sends 1x measurement objects to configure the user's device. The device performs the IRAT measurements using the measurement gaps configured by the eNodeB and reports the measured signal strength(s). (Figure 13)

If a 1x cell of sufficient signal strength is detected during the IRAT measurements, the eNodeB triggers the e1xCSFB procedure by sending a special RRC message (*HOFromEUTRAPrepRequest*). If no 1x cell of sufficient

Figure 11

Device registration including e1xCSFB when on LTE

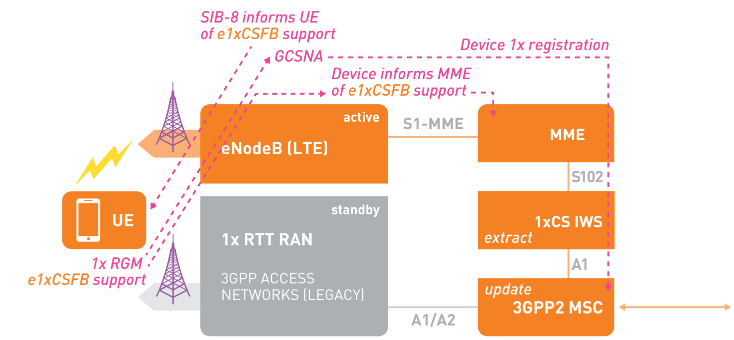


Figure 12

MME informs eNodeB of device e1xCSFB support

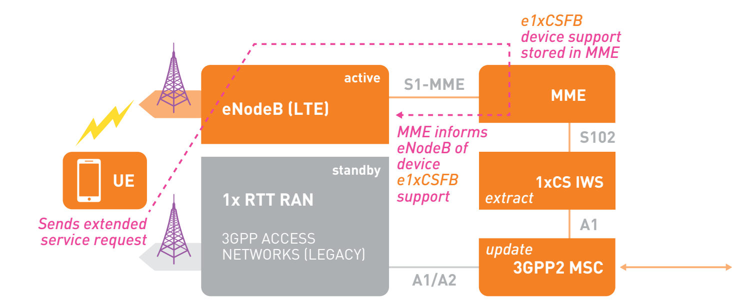
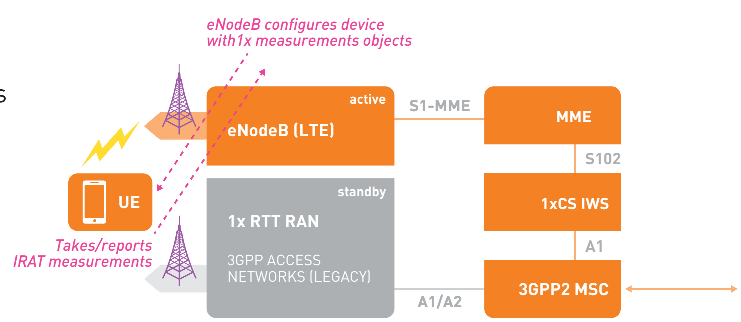


Figure 13

eNodeB and user device identify IRAT measurements



signal strength is detected, the eNodeB can choose either to configure another frequency or resort to the redirection-based 1xCSFB procedure, which is also available. Using the information sent from the eNodeB, the device forms the 1x Origination message (ORM) or 1x Page Response Message (PRM) depending on whether UE is initiating a voice call or responding to a tunneled 1x page. The 1x ORM or PRM is tunneled transparently to the 1xCS IWS through the GCSNA protocol. The eNodeB also appends the measured pilots to this message. Based on the received pilot measurements, the 1xCS IWS interacts with the 1x MSC to reserve a traffic channel in the measured cells. (Figure 14)

The 1xCS IWS conveys this information to the device using the Universal Handoff Direction Message (UHDM) tunneled through the LTE network using the GCSNA protocol. (Figure 15)

Upon receiving the UHDM, the device tunes to the 1x frequency and pilots in the message. This procedure is similar to a hard handoff in 1x-only networks. The eNodeB monitors to determine if the user's device re-establishes a Radio Resource Control Connection to LTE. If, after an operator-configurable amount of time, no re-connection is attempted, the eNodeB informs the MME that the user's device has successfully moved to a 1x voice call. In response, the MME suspends the user device's context on LTE until it returns to LTE after the voice call ends. This suspension prevents wasting LTE resources paging the device when it is not on LTE. (Figure 16)

Post-call network selection

After the call ends, the user device can either remain on 1x or return to LTE.

If remaining on 1x, the user device can return to LTE through cell-reselection (if supported by the network) or better system reselection (BSR). There are a few drawbacks of staying on 1x after the 1xCSFB call ends. The first drawback of staying on 1x is that the user's device must perform 1x registration over the 1x network and re-perform the 1x registration over the S102 tunnel upon return to LTE. In addition, the device will try to acquire co-located EVDO systems when it camps on 1x. If EVDO is acquired before the device moves to LTE, the packet data network context will be moved from LTE to the enhanced high rate packet

Figure 14

eNodeB triggers e1xCSFB to device

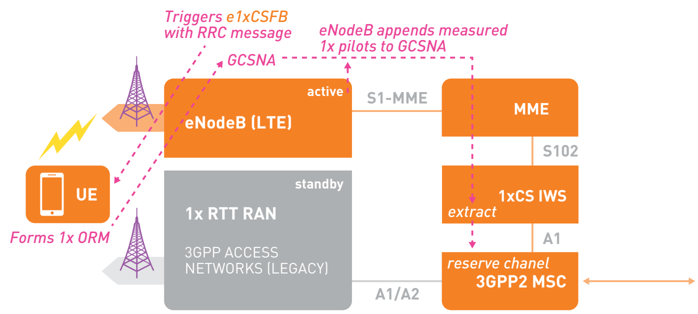


Figure 15

1xCS IWS sends UHDM to user's device

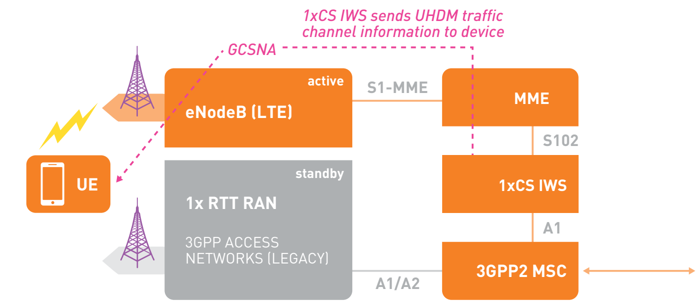
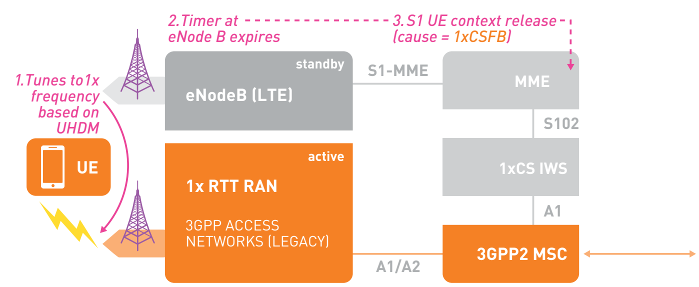


Figure 16

User device tunes to 1x; LTE suspends



data enhancement of 1xEVDO and then back to LTE. If EVDO is not acquired within a specified time period, the user's device will attempt to move the data context from LTE to 1x, causing a loss in IP continuity, since the same IP address cannot be maintained across LTE and 1x.

All this extra signaling can be prevented by an immediate return to LTE after the 1x call ends.

Immediate return to LTE can be achieved by invoking an out-of-service scan procedure based on the provisioned multi-mode system-selection files. If the device is within range of the preferred LTE network, the device will return to LTE and perform a tracking-area update to resume the suspended context. If the device is no longer within range of LTE, the LTE scan will fail and the device will camp on 1x. The drawback of this approach is the time spent scanning LTE before camping on 1x in the case where the device has moved out of coverage. This time depends on the number of LTE bands supported by the device. One workaround to control this delay is to enforce a hard limit on time spent scanning for LTE after the call ends.

Outgoing call setup time

The additional steps in switching from LTE to 1x networks for outgoing voice calls using 1xCSFB would be expected to incur a penalty in outgoing call setup times. To quantify call setup time differences between 1xCSFB and legacy 1x, measurements of call setup times have been collected for mobile-originated (outgoing) voice calls in live 1x networks with commercial infrastructure, averaged over a variety of good and poor radio conditions.

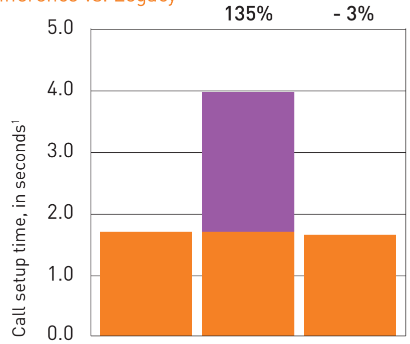
As summarized in Figure 17, the time penalty for outgoing call setup time using 3GPP Release 8 1xCSFB redirection is substantial—4 seconds—more than doubling the native 1x call setup time.

In sharp contrast, there is no call setup time penalty using 3GPP Release 9 e1xCSFB handover, which actually performed slightly better than native 1x call setup, and almost 2 1/3 seconds better than redirection-based 1xCSFB.

Figure 17

Outgoing call setup times, legacy 1x, LTE to 1xCSFB (redirection) and e1xCSFB (handover), in seconds

	Native 1x Legacy	Redirection 3GPP R8 1xCSFB	Handover 3GPP R9 e1xCSFB
Extended service request on LTE		0.45	0.45
Redirection + stack switch		0.15	
1x measurements while on LTE			0.25[1]
UHDM assignment			0.55
Stack switch + tune to 1x frequency			0.40
Acquire pilot on redirected frequency		0.20	
Acquire overheads on redirected frequency		0.64	
Channel hash + acquire overheads on hash-to frequency		0.85	
Access procedure to get traffic channel		1.70	
Total	1.70	3.99	1.65
Difference vs. Legacy		2.29 135%	-0.05 - 3%



[1]0.15 seconds for one measurement; 0.1 second buffer to account for probability of multiple measurments

Incoming calls setup time

For mobile terminated (incoming) voice calls, measurements of call setup times have also been collected in live 1x networks with commercial infrastructure, averaged over a variety of good and poor radio conditions.

As summarized in Figure 18, the time penalty for incoming call setup time using 3GPP Release 8 1xCSFB redirection is relatively small—about ½ second—11% longer than native 1x call setup time.

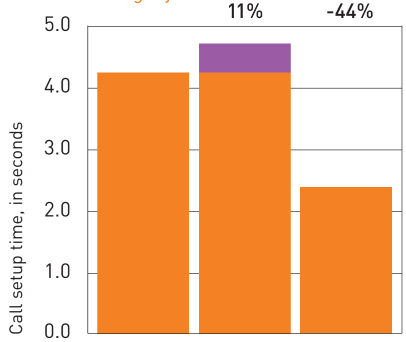
In an even sharper contrast than for outgoing calls, 3GPP Release 9 e1xCSFB handover actually reduces incoming call setup time by almost half compared to native 1x call setup, and about 2 1/3 seconds better than redirection-based 1xCSFB.

The e1xCSFB procedures have a significant advantage due to the much smaller DRX (1.28 second) cycle employed by the LTE network compared to the slot (5.12 second) cycle employed by 1x networks.

Figure 18

Incoming call setup times, legacy 1x, LTE to 1xCSFB (redirection) and e1xCSFB (handover), in seconds

	Native 1x Legacy	Redirection 3GPP R8 1xCSFB	Handover 3GPP R9 e1xCSFB
1x page message delivery	2.56		
LTE page delivery		0.64	0.64
Extended service request on LTE		0.55	0.55
Redirection + stack switch		0.15	
1x measurements while on LTE			0.25
UHDM assignment			0.55
Stack switch + tune to 1x frequency			0.40
Acquire pilot on redirected frequency		0.20	
Acquire overheads on redirected frequency		0.64	
Channel hash + acquire overheads on hash-to frequency		0.85	
Access procedure to get traffic channel	1.70	1.70	
Total	4.26	4.73	2.39
Difference vs. Legacy		0.47 11%	-1.87 -44%



Dual radios vs. single radios

3GPP2 operators deploying LTE are considering both dual radio (SV-LTE) and single radio (1xCSFB) devices for future deployments. Current deployments are based on single radio SV-LTE, and some major operators will be deploying 1xCSFB devices within the next year.

Narrowing the focus to 3GPP Release 9 handover e1xCSFB, summarized in Figure 19, single radio e1xCSFB devices have advantages on the following seven metrics:

- Slightly better outgoing call setup time
- Dramatically better incoming call setup time
- Lower power consumption and longer battery life due to single domain camping
- Lower device cost, needing only 1 Tx chain
- Looking to service other operators' subscribers, operators deploying 1xCSFB infrastructure can accept all devices as inbound roamers
- For network efficiencies, operators deploying 1xCSFB infrastructure can use the S102 tunnel to offload SMS from the 1x RAN without having to deploy IMS
- Looking to the future, operators deploying 1xCSFB infrastructure can reuse S102 infrastructure for SRVCC from VoLTE to 1x and so can deploy VoLTE prior to nationwide LTE coverage

Dual radio SV-LTE devices have advantages on the following three metrics:

- Simultaneous voice and LTE data user experience prior to VoLTE
- Delays the cost of deploying the S102 tunnel
- Devices can roam into most other LTE networks, though some LTE/1x band combinations need special consideration

The choice between the dual radio SV-LTE path and the single radio 1xCSFB path will vary from one operator to another. Some of the key factors to consider are:

- Does the operator need to rely on the LTE coverage of non-1xCSFB operators to provide their devices with sufficient LTE footprint?
- How long do the higher costs of dual radio SV-LTE devices need to be incurred, and when do they exceed 1xCSFB network upgrade costs? Essentially, how long will it be until VoLTE-only devices can be supported?
- Does the operator plan to deploy VoLTE prior to nationwide LTE coverage?
- How important is simultaneous voice and data in 1x call environments?

Finally, some operators may deploy 1xCSFB for most of their devices, but also offer a few SV-LTE devices for customers who require simultaneous voice and data.

Figure 19

Comparisons of dual radio SV-LTE with single radio e1xCSFB, in seconds

Advantage (orange) Disadvantage (grey)

Performance Metric	Dual Radio SV-LTE	Single Radio + e1xCSFB
Outgoing call setup time	.05 seconds slower	.05 seconds (3%) faster
Incoming call setup time	1.87 seconds slower	1.87 seconds (44%) faster
Standby power consumption	1x+LTE idle standby	LTE idle standby ONLY
Simultaneous voice+data	Yes	No
Device cost	Higher	Lower
Incremental network cost	No network impact	Additions/upgrades
Outbound roaming	No network impact[1]	Needs visited LTE network support for e1xCSFB[2]
Inbound roaming	1x voice and data on DO[3]	All inbound roamers accepted
SMS	Need IMS to offload from 1x network	Reuse S102 to offload from 1x network
Future-proofing	VoLTE will require nationwide LTE	Reuse S102 for SRVCC (VoLTE)

[1] Roaming supported if 1x and LTE roaming agreements are in place. Some 1x and LTE band combinations may need special attention.
[2] If LTE roaming is not in place, the device will camp on 1x network, if 1x roaming agreement is in place.
[3] Data on DO if appropriate PRL information configured

These SV-LTE devices can use 1xCSFB procedures while idle and selectively turn on SV-LTE when on a voice call. SV-LTE devices do not automatically have 1xCSFB capability; this would have to be specifically included in the specifications of the device requested by the carrier.

1xCSFB with LTE RAN sharing

The LTE architecture allows operators to share eNodeBs and reduce the cost of providing LTE services to users.

One use case of considerable interest is a wholesale operator deploying an LTE network and providing services to other mobile operators that have 3G-only networks in a specific coverage area. Each mobile operator may want its users to fall back from this common LTE network to its own 3G core network during the e1xCSFB procedure. Since many operators are interested in this feature, the 3GPP standards are being enhanced to enable 1xCSFB with RAN sharing. These changes are being targeted for Release 12, with these fundamental solution building blocks:

- *Existing feature:* The SIB-1 contains the PLMN-IDs of the different operators sharing the LTE eNodeB
- *Existing feature:* The UE selects the best PLMN-ID among the ones contained in SIB-1, based on PLMN selection rules [3GPP TS 23.122] and indicates the selected PLMN-ID to the LTE network in RRC signaling
- *Existing feature enhanced:* The eNodeB selects the MME based on the PLMN-ID provided by the user's device and 1x registration parameters transmitted in the default block of the SIB-8
- *Existing feature enhanced:* The MME selects the IWS based on the PLMN-ID provided by the user's device or subscription
- *New feature:* The SIB-8 is enhanced to transmit the multiple instances of the 1x registration related parameters, one for each 3G operator connected to the shared LTE network. The S102 registration is routed to the appropriate IWS selected.

Using this approach, each operator can have its users fall back to its 3G core network during the e1xCSFB procedure while sharing access to a common or third party LTE RAN.

Conclusions

Dual radio SV-LTE and single radio 1xCSFB each have their own advantages and disadvantages.

Dual radio SV-LTE has some near-term advantages in network infrastructure cost, simultaneous voice and data experiences and outbound roaming.

Single radio 1xCSFB has near-term advantages in call setup time, device cost, device size, battery life, SMS traffic efficiencies and inbound roaming.

Longer term, the network upgrades to support single-radio 1xCSFB solution also provide the infrastructure for later phases of LTE voice evolution that add additional operator network capacity gains and user experience enhancements, such as VoLTE with SRVCC. Even as VoLTE is initially launched, VoLTE handsets will continue to require CSFB for roaming.

The choice between the two approaches depends on a clear assessment of each operator's unique situation and vision for the future of LTE deployment in their own networks and the in the networks of their partners and competitors.

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