Supporting Voice over LTE: Solutions, Architectures, and Protocols

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***Abstract*—Modern cellular networks are expected to support both voice and growing volume of data traffic. The rapid growth in data traffic has promoted network operators to move to Long Term Evolution (LTE), a 4^{th} generation of wireless network infrastructure. The LTE architecture does not support native circuit switching services and relies on the IP Multimedia Subsystem (IMS) for supporting voice and Short Messaging Service (SMS). Unfortunately, the uptake of IMS has not been as rapid as expected and there are almost no operators that have an IMS core. This poses a major issue for operators who wish to deploy LTE in the near future. In particular, since voice and SMS drive a majority of revenue, the service providers are concerned with the voice quality, call continuity, and reliable SMS delivery in the deployed LTE networks. In this paper, we analyze several contending approaches to delivering voice services to a LTE based architecture. Each approach will be detailed through sequence diagrams to explain how voice and SMS services are rendered. We compare the proposed solutions in terms of complexity, cost, features, and interoperability.**

I. Introduction

Voice and Short Messaging Service (SMS) are the primary sources of revenue for wireless operators; however, the data traffic is consuming most of the bandwidth. This trend is new, and the disparity between data and voice bandwidth consumption is expected to grow. This has forced operators to plan on deploying a 4^{th} generation of wireless network infrastructure, based on packet switching. However, this new architecture does not natively support voice or SMS delivery. Operators are now faced with evaluating, selecting, and implementing one of several competing strategies to deliver voice and SMS over this new network architecture.

Most of the recent growth in data traffic can be attributed to the rapid uptake and usage of smart phones and tablets. Cellular broadband usage has far outpaced all expectations, resulting in an increasing demand on network operators. Outages of cellular networks are are now regularly in the media. To alleviate the current network strain, the network operators are deploying more radio towers, establishing a denser footprint, and using 3G offload strategies in high density areas with Wi-Fi technology.

As data usage eclipses voice on the cellular networks, it makes sense to re-architect the network with a focus on data traffic; preserving the existing revenue of voice and SMS. A vast majority of network operators and telecommunication vendors have decided to deploy Long Term Evolution (LTE), as specified by the 3^{rd} Generation Partnership Project (3GPP) in Release 8, to support this new trend in cellular usage. LTE is based on packet switching, and leverages the flexibility and interoperability offered by the Internet Protocol (IP).

IP Multimedia Subsystem (IMS) is a reference architecture that was specified by 3GPP to support a rich set of multimedia services delivered over a Packet Switched (PS) network. The IMS specifications outline a rich collection of functional elements and interactions in support of a wide variety of multimedia services. IMS was originally intended to carry the voice traffic of 3G networks; however, no major IMS deployment activity has commenced to date.

Deploying LTE networks poses several major challenges. First, LTE only provides packet based access to mobile devices, with no native support for Circuit Switched (CS) network access. As a result, voice calls and SMS messaging, which are a major source of revenue for network operators, are not natively supported by LTE. Second, as many operators quickly move to LTE, LTE deployment outpaces the deployment of IMS. As a result, certain operators are currently faced with the possibility of deploying LTE access networks without IMS cores. This is acceptable for some operators who wish to primarily offer mobile data access; however, a majority of carriers want to provide access to their primary revenue applications such as voice and SMS. This presents an inversion of service for traditional wireless applications such as voice and SMS. Operators without a IMS voice architecture cannot serve LTE based mobile devices with voice or SMS.

Solution overview. Currently, there are several proposed solutions to this problem that include: Circuit Switched Fall Back (CSFB) [1], Voice over LTE via GAN (VoLGA) [2], IMS [3], Voice over LTE (VoLTE) [4], and Over-the-Top. CSFB is a proposal by the 3GPP standards body that implies LTE radio coverage would always overlap with legacy radio access. Whenever voice services are necessary the User Equipment (UE) and network would work together through LTE to decide to 'Fallback' to the legacy radio network for CS access. VoLGA is a proposal by an industry led forum that aims to let the UE establish tunnels over LTE that will emulate a CS connection to a legacy Mobile Switching Center (MSC). IMS defines a Session Initiation Protocol (SIP) based multimedia delivery solution that works over PS networks. VoLTE is a subset of IMS that focuses on voice and SMS interactions at key points in the network. Over-the-Top solutions are quite similar to Voice over IP (VoIP) services offered over the

Acronym	Description	Acronym	Description
BGCF	Breakout Gateway Control Function	NAS	Non Access Stratum
CS	Circuit Switched	NNI	Network to Network Interface
CSCF	Call Session Control Functions	P-CSCF	Proxy CSCF
CSFB	Circuit Switched Fall Back	PDN-GW	Packet Data Network Gateway
DHCP	Dynamic Host Configuration Protocol	PS	Packet Switched
DL	Downlink	PSTN	Public Switched Telephone Network
DTMF	Dual-Tone Multi-Frequency	RRC	Radio Resource Control
EIR	Equipment Identity Register	RTP	Realtime Transport Protocol
eNB	Evolved NodeB	S-GW	Serving Gateway
GA-CSR	Generic Access - Circuit Switched Resource	S1AP	S1 Application Protocol
GA-RC	Generic Access - Resource Control	SCTP	Stream Control Transmission Protocol
GA-RRC	Generic Access - Radio Resource Control	SDP	Session Description Protocol
GAN	Generic Access Network	SGW	Signaling Gateway
GERAN	GSM EDGE Radio Access Network	SIP	Session Initiation Protocol
GSMA	GSM Association	SIP-AS	SIP Application Server
GTPv1-U	GPRS Tunneling Protocol Version 1 User	SLF	Service Location Function
GTPv2-C	Evolved GPRS Tunneling Protocol version 2 Control	SMS	Short Messaging Service
HSS	Home Subscriber Server	UE	User Equipment
IMS	IP Multimedia Subsystem	UL	Uplink
IP	Internet Protocol	UMA	Unlicensed Mobile Access
LTE	Long Term Evolution	UMTS	Universal Mobile Telecommunications System
MGCF	Media Gateway Control Function	UNI	User to Network Interface
MGW	Media Gateway	UTRAN	UMTS Terrestrial Radio Access Network
MME	Mobility Management Element	VANC	VoLGA Access Network Controller
MRFC	Media Resource Function Controller	VoIP	Voice over IP
MRFP	Media Resource Function Processor	VoLGA	Voice over LTE via GAN
MSC	Mobile Switching Center	VoLTE	Voice over LTE

TABLE I
ACRONYMS

Internet independent of broadband providers. Finally, there are certain vendors that believe a more proprietary approach to serve legacy/circuit voice applications is appropriate.

The goal of this paper is to describe the basic operation of these contending approaches that deliver legacy circuit based voice services to a LTE based architecture. Each approach will be explored through sequence diagrams; explaining how the basic voice services are rendered. We also compare and contrast each solution with its alternatives. For convenience, Table I lists all acronyms used in this paper.

II. Background

A. LTE

LTE is a wireless networking technology designed to provide subscribers with a secure high performance wireless network experience. The primary assumption of LTE is that all subscriber applications will use IP. LTE is described in many specifications across thousands of pages; however, most of the details of LTE can be distilled into three basic concepts: managing subscribers (or UE), managing bearer tunnels, and using bearer tunnels. Because LTE is an IP-only network, the primary job of the network is to provide IP packet delivery for the UE; this is the job of a bearer tunnel. The UE uses bearer tunnels to send and receive IP packets while moving through and between LTE networks. Bearer tunnels are adjusted to follow the UE as it moves through and between networks to always ensure a path for packet delivery. Finally, the UE must authenticate, authorize, and register themselves with the network in order to be tracked, create, and use these bearer tunnels.

The 3GPP defines functional element protocol interactions as interfaces or reference points. These interfaces are typically

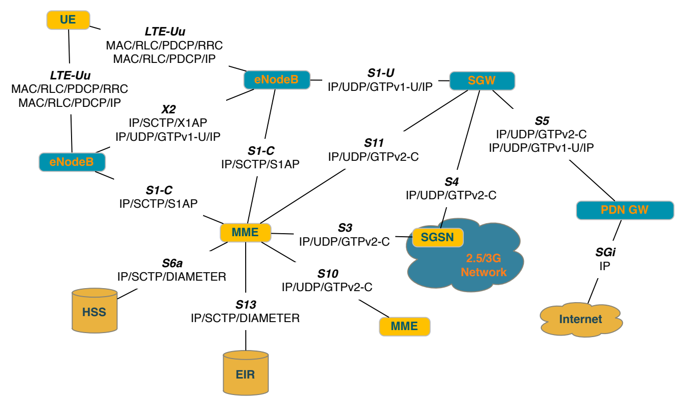

Fig. 1. LTE Architecture and Protocols

given names of the form: S1, X2, S11, etc. Figure 1 depicts the functional elements of a LTE architecture and displays their reference point names. This figure also details the actual protocols being used over these reference points in an effort to be clear about their nature. The following paragraphs will describe how the three main functions of LTE are carried out by the LTE network elements depicted in Figure 1.

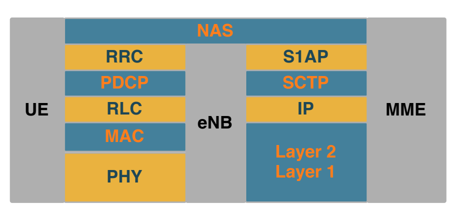

Fig. 2. UE to MME Control Signaling

The Mobility Management Element (MME) authenticates, authorizes, and manages subscriber UE registrations. The MME to UE control signaling protocol layers are depicted in Figure 2. The MME and UE communicate using the Non Access Stratum (NAS) protocol [5], which is routed between the MME and UE through the Evolved NodeB (eNB). The eNB is the smart radio base station that is used in the LTE architecture. The eNB uses the S1 Application Protocol (S1AP) [6] to signal with the MME and carry NAS messages to and from the MME. S1AP is carried over a Stream Control Transmission Protocol (SCTP) [7] connection between the eNB and the MME. The eNB uses the Radio Resource Control (RRC) protocol [8] signal the UE and to carry NAS messages to and from the UE over the air interface. The Home Subscriber Server (HSS) is a database used by the MME to retrieve subscriber credentials and store relevant UE information. The MME and HSS interaction takes place using the DIAMETER protocol [9] over a SCTP connection. The MME can perform authorization on the equipment itself by querying the Equipment Identity Register (EIR) in a similar manner as interacting with the HSS.

The MME is responsible for creating and managing bearer tunnels on behalf of the UE as it moves through the network. Bearer tunnels map the UE across a specific radio bearer to a eNB, then through a GPRS Tunneling Protocol Version 1 User (GTPv1-U) [10] tunnel from the eNB to a specific Serving Gateway (S-GW), and then to a terminating Packet Data Network Gateway (PDN-GW). As the UE moves through the network the bearer tunnel will need to shift to new eNBs and S-GWs in order to maintain a connection. The MME manages bearer tunnels through the eNB using the S1AP protocol, and through the S-GW using the Evolved GPRS Tunneling Protocol version 2 Control (GTPv2-C) [11] over UDP. GTPv2-C messages are proxied by the S-GW to the PDN-GW to manage bearer tunnel termination.

Finally, UE IP traffic is carried over the bearer tunnel, which connects the UE and the PDN-GW. This IP traffic is encapsulated in the GTPv1-U protocol. The eNB will take traffic from a radio bearer and place it into the appropriate GTPv1-U tunnel over UDP, which will then be forwarded to the S-GW. The S-GW will forward it to the appropriate PDW-GW, where it will be de-encapsulated and routed. The reverse flow follows a similar procedure. This tunnel provides the UE with a static interface for IP traffic even as the device moves through the deployed LTE network.

B. IMS Architecture

IMS is a reference architecture developed by the 3GPP organization to support IP based multimedia sessions. The core of IMS is based on SIP, and Realtime Transport Protocol (RTP). Devices can register their presence with the IMS network, receive messaging based on specific event types they subscribe to, and initiate and receive real-time multimedia sessions (voice session, video session, etc). IMS defines specific processes for establishing subscriber authenticity, session routing, inter-carrier routing, inter-carrier-roaming, inter-carrier charging, and per session based QoS.

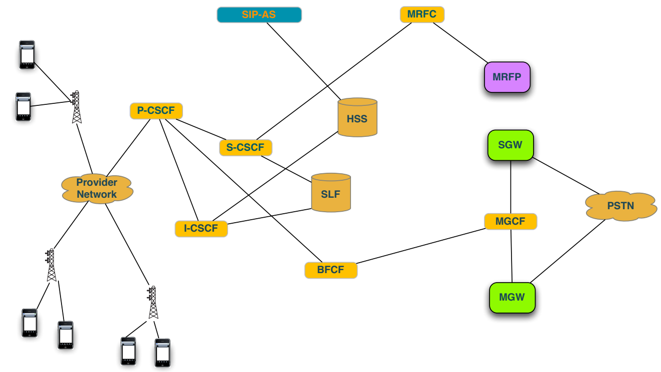

Fig. 3. IMS architecture

The IMS architecture's functional decomposition is represented in Figure 3. The core of a IMS network is powered by Call Session Control Functions (CSCF). These servers provide a series of SIP services such as: registration, authentication, signaling message compression, and service routing. The Subscriber Location Function (SLF) and HSS provide registry and location based lookups for the architecture as a whole. The Breakout Gateway Control Function (BGCF), Media Gateway Control Function (MGCF), Signaling Gateway (SGW), and Media Gateway (MGW) provide a IP interface to and from the Public Switched Telephone Network (PSTN). The Media Resource Function Controller (MRFC) and Media Resource Function Processor (MRFP) provide media resources for Dual-Tone Multi-Frequency (DTMF) capture/generation, audio mixing, transcoding, audio recording, etc. Finally, the SIP Application Server (SIP-AS) provides the ability to define custom services through a API [3].

IMS was originally intended to be the voice signaling and delivery platform for IP capable networks such as Universal Mobile Telecommunications System (UMTS) and LTE. However, deployment of the IMS architecture has not become a reality. The IMS architecture is complicated and deployment requires a substantial investment in network equipment, operational knowledge, and time. Because UMTS can still use CS based voice, the additional cost of IMS to deliver voice services has not been seen as a justifiable expense. However, LTE provides no CS facilities and forces the issue of voice support.

III. Solution Landscape

IMS has been the default solution to provide voice and SMS services over any IP network (LTE included); however, due to availability, complexity, and familiarity with IMS, network operators are investigating alternative solutions for LTE network deployments. These alternative solutions include: CSFB, VoLGA, VoLTE, and Over-the-Top.

A. CSFB

Circuit Switched Fallback defines a mechanism for mobile devices to use the legacy network for voice traffic in place of an IMS architecture [1]. Mobile calls will take place over a existing 2.5G (GSM EDGE Radio Access Network - GERAN) or 3G (UMTS Terrestrial Radio Access Network - UTRAN) network instead of over LTE.

A mobile device will connect to the LTE network in the same way as a standard LTE UE, but it will use a combined attach procedure and its capabilities will advertise CS fallback. The MME will then signal a location update to an MSC in the legacy GERAN or UTRAN network, which will hold the location of the mobile device in terms of CS services. The MSC and MME will serve as a bridge between the legacy and LTE networks.

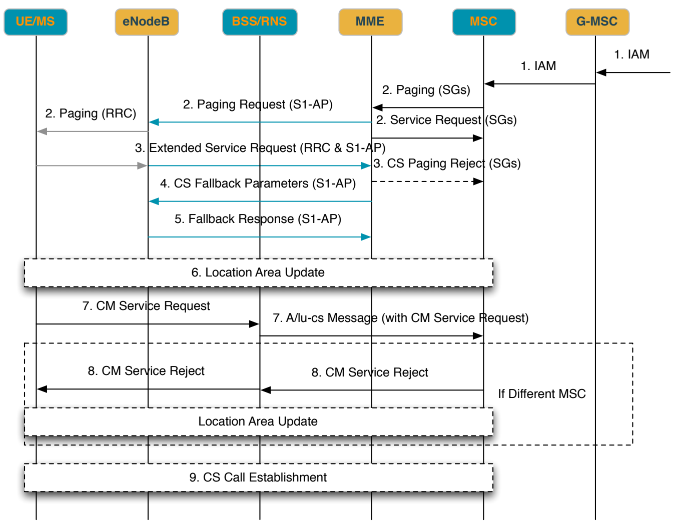

Fig. 4. Mobile Terminated CSFB

Mobile calls can be either mobile originated or terminated, but in either case, the UE must switch to the legacy network and disconnect from the LTE network in order to complete the call. Figure 4 demonstrates the mobile terminated case. The call starts in step 1 with an incoming IAM message on the legacy network. This is translated in step 2 to a paging request by the MSC and forwarded to the UE over the SGs interface to the MME, over S1AP to the eNB, and finally to the UE using RRC. Upon receipt of the paging request by the MME, it responds with a service request if the UE is in range, and the MSC uses this response to send alerting to the calling party. The UE responds in step 3 with an extended service request when the call is accepted or rejected using RRC to the eNB and S1-AP to the MME. In the rejected case, the MME sends a CS paging reject to the MSC and the sequence terminates. When the call is accepted, it requests the CS fallback parameters. The MME responds with the CS fallback parameters. This may trigger a handover of any packet switched traffic, if present and supported. The UE then connects to the legacy network in step 6, triggering location updates to the waiting call's MSC, attempts to complete the call in step 7. If the MSC is different than the one originally routing the call, the MSC will reject the call request, and issue a location update to change the call to this MSC in step 8. Finally, in step 9, the call is completed. When a call is mobile originated, the same procedure is followed, but the UE starts with the Extended Service Request in step 3.

Receiving SMS messages do not require a fallback to the legacy network. The paging requests are forwarded through the LTE network in the same manner of the call, but instead of the UE transitioning to the legacy network to complete the request, it establishes a service request over the LTE network to the MME, and the message is forwarded from the MSC to the MME over the SGs interface, which is then forwarded to the UE over NAS. A mobile originated SMS messages also involves a service request over the LTE network to the MME. The SMS is sent to the MME over NAS, which forwards the message to the MSC over the SGs interface, where the message is routed over the legacy network, and the report is send back via the reverse path.

B. VoLGA

VoLGA proposes to let a legacy MSC provide voice and SMS services to LTE UEs through either a GERAN A interface or UTRAN Iu-CS interface. This concept originates with Unlicensed Mobile Access (UMA). UMA was developed to support 2.5G/3G network extension using Wi-Fi as network access. Handsets that supported Wi-Fi would establish a IPSec ESP tunnel to a tunnel terminator in a service provider network that directly connected to the legacy MSC. The tunnel terminator would also provide some interworking functionality to allow these IP based endpoints to appear as if they were connecting to the MSC using legacy interfaces. UMA was submitted and accepted as a standard in the 3GPP standards body and was renamed Generic Access Network (GAN) for Release 6.

VoLGA was designed to have minimal impact on existing networks; however, it does require special support in the UE and the introduction of the VoLGA Access Network Controller (VANC). The primary responsibilities of the VANC are: terminate IPSec ESP tunnels from the UEs, provide NAS signaling delivery between the UE and MSC, and establish and map voice traffic between the UE and MSC. The VANC performs authentication and authorization on incoming IPSec ESP tunnels using a AAA server via the Wm interface. The VANC can connect to a GERAN network's MSC using the A interface, or a UTRAN network's MSC using the Iu-CS interface. Also, the VANC has the ability to interact with the LTE network and request QoS for VoLGA voice calls.

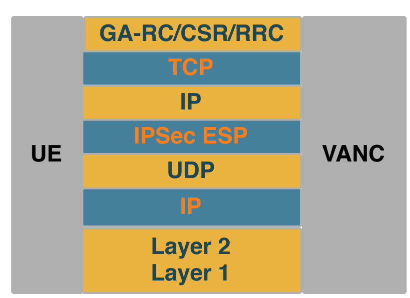

Fig. 5. VoLGA Signaling

A UE accesses the VoLGA service through its Dynamic Host Configuration Protocol (DHCP) process. It resolves the address of its VANC server and establishes a IPSec ESP tunnel. It then establishes a TCP connection to carry several signaling protocols: GA-RC, GA-CSR, and GA-RRC. Generic Access - Resource Control (GA-RC) is used to manage UE registrations with the VoLGA service, negotiate the UE's operational mode, and provide keep-alives for the UE. A UE negotiates its operational mode so it can integrate with a MSG in GERAN A-mode, UTRAN Iu-CS mode, or both. Generic Access - Circuit Switched Resource (GA-CSR) allows for interworking with GERAN, while Generic Access - Radio Resource Control (GA-RRC) allows for interworking with UTRAN. Both GA-CSR and GA-RRC messages are used to establish voice bearers, tunnel NAS messages, and interwork with MSC signaling. Figure 5 depicts the signaling stack between a UE and the VANC server [12].

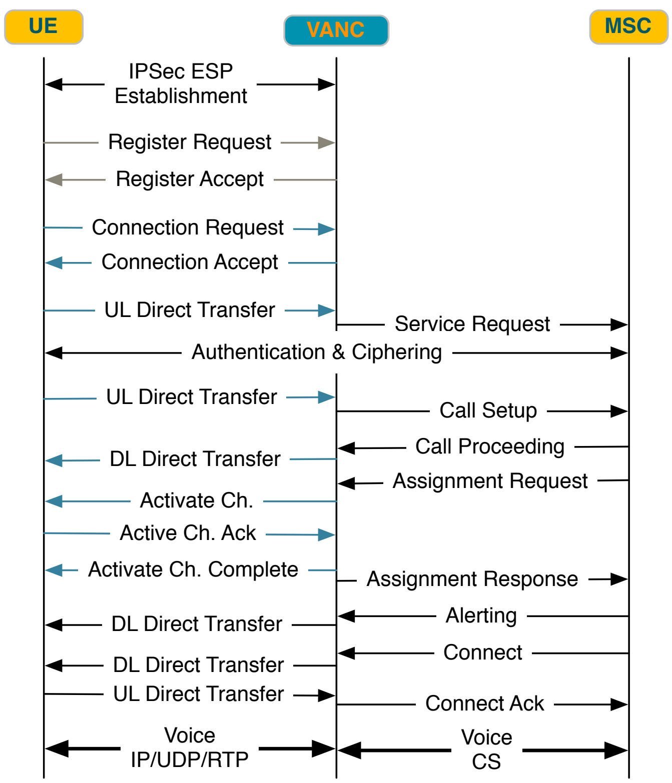

Fig. 6. Mobile Originated VoLGA

Once a UE is registered with the VoLGA network it can request connection with the MSC using either GA-CSR or GA-RRC depending on the negotiated mode of operation. Once a connection exist NAS messages can be tunneled between the MSC and the UE using Uplink (UL) and Downlink (DL) Direct Transfer messages. A UE originated call will request service with a UL Direct Transfer, which will start the authentication and ciphering process. Call signaling is then tunneled between the UE and MSC using direct transfers. Voice bearer is handled outside of the context of the IPSec connection between the UE and MSC. The UE and VANC will send and receive voice bearer using RTP. Voice is queued and framed at both the VANC and UE into RTP packets, which are forwarded to the negotiated UDP port and IP addresses. These address and port combinations are negotiated during the Activate Channel sequence between the VANC and UE. The VANC will then switch voice traffic between MSC's circuit and UE's RTP flows. This origination sequence is depicted in Figure 6.

Termination calls are supported in a similar manner except for the addition of the Paging message. Both GA-CSR and GA-RRC support a paging request which is used to indicate a inbound service request. SMS messages can be handled in the VoLGA architecture through embedding of legacy SMS messages in Direct Transfer messages.

C. VoLTE

VoLTE is a initiative led by the GSM Association (GSMA) that aims to define exactly how an LTE operator deploys IMS to carry voice traffic. The initiative plans to develop specifications that clearly outline three types of IMS voice interactions: User to Network Interface (UNI), Network to Network Interface (NNI), and a roaming interface. These specifications would provide a clear list of IMS features that must be supported in order to provide a acceptable voice service. The UNI interface is addressed through the IR92 specification that the GSMA published in March of 2010 [4]. The organization plans on releasing a NNI interface by mid-2010, and a roaming interface by the beginning of 2011.

The UNI specification presents a set of concrete requirements on IMS elements for a VoLTE architecture. For signaling the UE must support registration, origination, and termination as specified in the main IMS SIP specification [3]. Signaling compression must be used between the UE and the Proxy CSCF (P-CSCF), and it mandates a list of supplementary services (Hold, Message Waiting Indicator, etc). It requires the support of 'Preconditions' through the SIP Requires header. This header allows SIP devices to negotiate required SIP features during signaling interaction. It gives further requirements on specific Session Description Protocol (SDP) offer/answer sequences, RTP profiles, and RTCP usages. Generally, the UNI specification dictates a list of mandatory compliance sections from 3GPP specifications and outlines how certain features are to be used.

D. Over The Top

Finally, any VoIP vendor can provide 'Over-the-Top' voice service to any LTE network user. The VoIP vendor would treat the network no differently than any other IP access medium. This solution would prohibit itself from supporting native handoff with legacy radio network such as GERAN and UTRAN. Handoff is possible through 'Tromboning', which is establishment of a default PSTN call-leg for non-LTE roaming, and a secondary VoIP call leg for LTE roaming. A AS will then switch media between the call legs based on the current location of the UE. But this technique is limited due to the availability of system level API access on handsets. Also, this technique requires double bandwidth for every active call. LTE providers can provide enhanced QoS for selected VoIP vendors by defining any flow to the VoIP vendor's network address range would receive a dedicated bearer with QoS via the LTE's PDN-GW and/or PCRF capabilities.

IV. Solution Comparison

There are currently four architectures that can provide voice and SMS services over a LTE network: Over-The-Top, VoLGA, CSFB, and VoLTE. Each solution presents different operational and technical tradeoffs.

	Handoff	Overlap	Simultaneous V&D	UE Support	New Network Elements	Modify Network Elements
IMS/VoLTE	✓	X	✓	✓	✓	X
CSFB	✓	✓	／*	✓	X	✓
VoLGA	✓	X	✓	✓	✓	X
Over The Top	✓**	X	✓	✓	X	X

If packet handoff is supported
* Tromboning solution with 2 call legs

TABLE II
VOICE SOLUTIONS COMPARISON

Using an 'Over-the-Top' VoIP service is the simplest mechanism to delivery voice to a LTE subscriber. The LTE operator is only required to install a VoIP client in the UE. The LTE operator could even configure the LTE network to provide protected QoS service to these VoIP calls using existing LTE flow classification mechanisms. There is no obvious way of delivering traditional SMS in this architecture. Also, handoff to circuit only wireless networks is possible, but circuitous. This architecture is useful for a sedentary subscriber base that lives within the existing LTE coverage area.

VoLGA seems to be the best compromise between simplicity, operational cost, and leveraging legacy voice and SMS services. VoLGA requires UE support and the introduction of the VANC network element. The LTE network can be configured to provide protected QoS service to VoLGA calls using flow classification. This solution maximizes a operator's investment in network equipment and operational knowledge by reusing the GERAN/UTRAN network architecture.

CSFB is a interesting approach for serving voice and SMS on a LTE network. CSFB requires a continuous overlap of GERAN/UTRAN and LTE coverage. Its primary mechanism works by forcing a fallback to one of these legacy radio technologies for call origination and termination. While it is possible to have simultaneous voice calls and data sessions with CSFB, it is not clear that it will be practical. CSFB does not require introduction of new network equipment, but does require enhancements in the UE, MME, SGSN, and MSC to support properly. CSFB can not function without the presence of a fallback network that overlaps with LTE coverage, this makes it suspect as a serious long term candidate for voice and SMS delivery over LTE.

VoLTE is a specification that defines how to use IMS to carry voice and SMS over the LTE network. VoLTE requires the operator to deploy a VoLTE compliant IMS architecture. This is unlikely to be a challenge for vendors as they have been building IMS equipment for some time now. However, the NNI and roaming specification of VoLTE are not expected to be complete till the beginning of 2011. It will take some time for interoperability to be established between vendors upon completion of the VoLTE specifications. This means VoLTE will be the last solution to the game as LTE deployments have started in 2010.

V. Conclusion

Wireless broadband adoption and usage is growing beyond all expectations of operators and network equipment manufacturers. This growth has caused severe strain on the existing 2.5/3G wireless infrastructure, forcing carriers to deploy Wi-Fi based offload solutions in dense areas and upgrade their core with LTE. LTE will now be deployed before there are obvious solutions for carrying the bulk of cellular revenue bearing traffic (voice and SMS). There are several solutions being proposed to solve this problem: CSFB, VoLGA, VoLTE, and Over-The-Top. Over-The-Top is the simplest solution; however, it is limited in its mobile capabilities. VoLGA presents a good compromise for providing a traditional mobile voice and SMS experience over LTE while maximizing a carriers investment and knowledge of their traditional CS based MSCs. CSFB is a bridging strategy the uses legacy radio coverage to provide voice and SMS that cannot exist without 2.5/3G coverage coexisting with LTE. VoLTE represents a simplified version of IMS and establishes a new call control architecture that would allow the eventual decommissioning of 2.5/3G voice and SMS infrastructure.

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