# VoLTE*: A Lightweight Voice Solution to 4G LTE Networks

Guan-Hua Tu[†*], Chi-Yu Li[†*], Chunyi Peng[‡], Zengwen Yuan[†], Yuanjie Li[†], Xiaohu Zhao[‡], Songwu Lu[†]

[†] Department of Computer Science, University of California, Los Angeles, Los Angeles, CA 90095
[‡] Department of Computer Science and Engineering, The Ohio State University, Columbus, OH 43210
{ghtu,lichiyu,zyuan,yuanjie.li,slu}@cs.ucla.edu, {peng.377,zhao.1722}@osu.edu

## ABSTRACT

VoLTE is the designated voice solution to the LTE network. Its early deployment is ongoing worldwide. In this work, we report an assessment on VoLTE. We show that VoLTE offers no categorically better quality than popular VoIP applications in all tested scenarios except some congested scenarios. Given the high cost on infrastructure upgrade, we argue that VoLTE, in its current form, might not warrant the deployment effort. We sketch VoLTE*, a lightweight voice solution from which all parties of users, LTE carriers, and VoIP service providers may benefit.

## Keywords

Cellular Networks; Voice; VoLTE*

## 1. INTRODUCTION

Voice is a simple, yet vital service to billions of mobile users. It has been a killer application in mobile network since its origin. For sake of guaranteed quality of service (QoS), voice calls have been traditionally supported through circuit-switched (CS) technology, where a dedicated channel (or circuit) is established for the transmission of voice traffic. However, this scheme becomes invalid any longer, as mobile network is rapidly advancing to Long Term Evolution (LTE), the 4th-generation (4G) standard, which supports packet-switched (PS) technology only. As a result, voice service has to migrate from CS to PS, due to this fundamental, irreversible change in LTE network architecture.

VoLTE (Voice over LTE) is thus proposed to fulfill this evolution [1, 2]. Its design seems quite straightforward. It carries voice traffic in packets over the IP-based LTE network, no longer through an dedicated circuit. To facilitate voice communication, each VoLTE call also maintains a separate signaling session. This is akin to Voice-over-IP (VoIP) over the Internet. To ensure carrier-grade call quality comparable to CS calls, it leverages high-priority delivery offered by the LTE network for both signaling and voice sessions.

[*]The first two authors contribute equally to this work.



*HotMobile'16, February 26–27, 2016, St. Augustine, FL, USA.*



ISBN 978-1-4503-4145-5/16/02…$15.00

DOI: http://dx.doi.org/10.1145/2873587.2873604

While promising, VoLTE has been going through a bumpy ride in its deployment. After its first commercial launch in 2012 [3], only 20 carriers out of 480 LTE networks have deployed VoLTE by October 2015 [4]. Among them, most carriers do not offer massive deployment. For example, the first rollout in major US carriers (Verizon, AT&T, and T-Mobile) was in late 2014, but until now, its nationwide deployment has not been achieved yet [5,6]. In fact, most carriers kept on promising but deferring its public launch again and again [7].

Inspired by such strenuous deployment, we seek to explore why. Our goal is two-fold. First, we conduct an assessment on VoLTE and investigate whether it is worth the effort to deploy VoLTE based on its performance, deployment cost and operation complexity, as well as benefits offered to different parties; second, we explore whether there exists an alternative lightweight voice solution, achieving comparable voice performance but at lower cost. Intuitively, our study is motivated by one common wisdom. We believe that strenuous deployment is often associated with inherent technical hurdles beyond operations.

To this end, we first investigate the current VoLTE solution from its deployment cost and operational complexity. It does require sophisticated support at the infrastructure. Specifically, IMS (IP Multimedia Subsystem), as well as complex functions, are needed inside the LTE network, leading to heavy investment cost and operational complexity. We further compare performance of VoLTE and popular VoIP applications (*e.g.*, Skype, Hangouts) when running in the LTE network. To our surprise, we discover that VoLTE offers no categorically better quality than VoIP in most cases. Moreover, we identify that the key quality guarantee comes from its cellular-specific QoS management, irrelevant to complex IMS. This implies that it is possible to enable PS-based voice solution in a simpler form.

Consequently, we propose VoLTE*, a lightweight voice solution to 4G LTE networks. Its core idea is to largely retain the Internet VoIP scheme at the device, while leveraging the priority service offered by the LTE core network. The LTE network only needs to offer *modest (and existing)* support for priority services, without implementing complex IMS and auxiliary functions. Instead, we largely leverage the existing VoIP service over the top.

The rest of the paper is organized as follows. §2 describes basic background on VoLTE. §3 investigates the cost and performance of VoLTE. §4 and §5 present the design and discussion of VoLTE*, respectively. §6 compares with related work. §7 presents the future work and §8 concludes the paper.

## 2. VOLTE PRIMER

VoLTE (Voice over LTE) [1,2] is designated as the ultimate voice solution to the 4G LTE mobile users. It seeks to migrate the tradi-

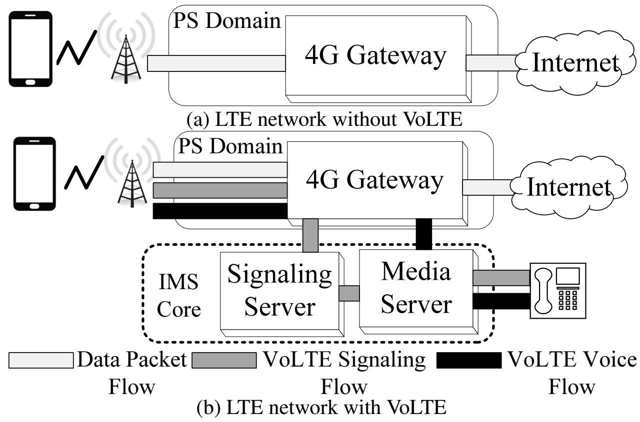



**Figure 1: LTE network architecture with(out) VoLTE.**

tional circuit-switched (CS) voice service to the packet-switched (PS) one. As illustrated in Figure 1, each VoLTE call maintains two communication sessions, one on the data plane and the other on the control plane. The control-plane session is to exchange the call signaling messages through the popular Session Initiation Protocol (SIP) [8]. The data-plane session handles the voice packet delivery via the Internet Real-time Transport Protocol (RTP) [9]; it is established on demand by the control-plane session. To ensure call quality comparable to typical CS calls, it leverages the multiple service classes (*e.g.*, the guaranteed bit rate and different priorities) offered by LTE. Both of VoLTE signaling and voice are delivered through the LTE's data channel that serves normal data services, but are offered higher priority than the data services.

Two subsystems in LTE networks are involved in the VoLTE operation. The first one is the IP Multimedia Subsystem (IMS) core, which is developed to support all-IP telephony and multimedia services [2]. It consists of the media gateway and the VoLTE server. The media gateway is to deliver real-time multimedia (*e.g.*, voice) traffic to VoLTE users, or to traditional telephony users. The VoLTE server provides call session control functions among the device, the media gateway and the 4G gateway. Note that the IMS core is not limited to the VoLTE support. It can be further upgraded to support other multimedia services, such as video conference call.

The second one is the existing packets-switched delivery subsystem. Its major component is the 4G gateway, akin to edge routers in the Internet. Its main role is to offer PS connectivity to and from the mobile device. To support VoLTE, the 4G gateway relays packets on both control and data planes between the device and the IMS core. In addition, the 4G gateway is also responsible for other control functions, *e.g.*, IP address allocation, packet filtering, policy enforcement and charging support.

## 3. VOLTE OR NO VOLTE?

We now take a step back by looking at alternative solutions to voice service over mobile networks. Our first choice is the popular Internet VoIP applications, which can directly operate over the IP-based LTE network.

Conceptually, the Internet VoIP solution follows design tenets different from VoLTE. It uses the best-effort service offered by the Internet, but relies on the end-device intelligence to improve voice quality. This works well with the increasing capabilities at the smartphone device. In contrast, VoLTE still mainly relies on the network infrastructure and phone hardware chip for call quality assurance, though it does migrate some functions to the phone software.

We next examine two other aspects of VoLTE operations: deployment overhead and call quality. We defer the discussion of the billing cost for users to Section 4. Our key finding is that VoLTE does not offer clearly better call performance than VoIP over LTE networks; in most of our tested cases, they are comparable. However, VoLTE incurs much higher deployment cost for operations.

### 3.1 Deployment and Operation Cost

The deployment is driven by two goals: voice call service among VoLTE users, and phone calls between VoLTE users and traditional phone users. Therefore, the deployment cost comes from two sources. The operator has to newly deploy the IMS core, and has to make changes on existing subsystems. In this case, two existing subsystems (PS domain, OAM (Operation, Administration and Maintenance) [10]) in the current 4G network infrastructure need to be updated. In addition, the CS domain components in 2G/3G infrastructure also need to be upgraded to support SRVCC (Single Radio Voice Call Continuity) [11], which migrates an ongoing 4G VoLTE call to the 2G/3G CS call once the user leaves the 4G coverage.

Specifically, the IMS core needs to be deployed. During VoLTE operations, it interacts with the mobile device, and potentially the legacy phone systems to translate the VoLTE signals and voice packets to the CS-based format. The PS subsystem in the LTE network needs to upgrade all four components: the user device, the 4G gateway, the base station and the mobility management entity. Its OAM needs to be updated to support new functions for VoLTE users: call charging and device authentication. In the legacy 2G/3G networks, the mobility component MSC (Mobile Switch Center) needs to be upgraded to interact with 4G VoLTE users.

In contrast, existing VoIP services (*e.g.*, Skype, Hangouts) do not require new deployment or infrastructure upgrade on the LTE network. We also note that translation servers are already deployed for years. They enable calls to traditional phone users from the VoIP user. However, we do identify a subtle issue for roaming users. Consider the scenario when the 4G network does not have full geographic coverage. When the user leaves the 4G coverage, the standard 4G→2G/3G handoff procedure is triggered. The ongoing VoIP call is then migrated from the 4G to the 2G/3G network. This process does not require infrastructure upgrade. Carriers leverage the existing servers from the VoIP service providers, and rely on the conventional handoffs to handle the insufficient 4G coverage. However, the charging function needs collaboration between the 4G carrier and the VoIP providers. In the current practice, Internet VoIP users are not billed by the service providers unless the calls are with traditional phone users.

### 3.2 Comparable Call Performance

We compare VoLTE and VoIP service (Google Hangouts is used) in terms of call setup time, voice performance and call drop rate. We conduct a medium-scale experiment: 10 static locations, 20 routes for mobility, and 50 people who are involved in the subjective test of voice performance. We show that they have comparable performance in all three aspects. However, VoLTE performs better in some congested scenarios . Note that we consider the locations with different signal strength based on user perception: strong ($> -90$ dBm), medium ($\in (-115, -90]$ dBm), and weak ($\leq -115$ dBm), which indicates the weakest level of the phone's signal strength icon.

Note that VoLTE is still at its early stage, so its performance may be further improved after more feedbacks are collected.

**Call Setup Time.** We examine the call setup time in four call scenarios: (1) VoLTE-to-VoLTE; (2) Hangouts-to-Hangouts; (3)

VoLTE-to-CS; (4) Hangouts-to-CS, where A-to-B represents that the caller with technology A makes a call to the callee with technology B. We thus assess both calls using the same technology and calls requiring PS/CS translation. The call setup time is the duration from the time the caller dials to that the callee's phone rings.

Figure 2 plots the call setup time for the tested four cases in two areas with weak and strong signal strength, where both the caller and the callee stay. The result of the medium signal strength is similar and omitted. We make two observations. First, the call setup time performed by Hangouts is comparable to that of VoLTE when both users use the same technology (*i.e.*, Scenarios (1) and (2)). They have median values around 5.0 seconds with smaller than 10% difference in three kinds of signal strength. Neither is better in all cases. Second, when the PS and CS translation is needed (*i.e.*, Scenarios (3) and (4)), Hangout requires 3.7–4.8 more seconds in the median values than VoLTE.

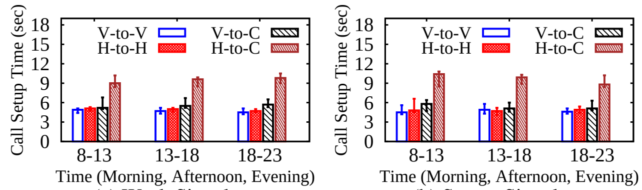
As a result, the control-plane performance by the signaling servers of VoLTE and Hangouts is comparable. However, when both PS and CS domains are involved, the translating gateway in the LTE network yields better performance than the Hangouts service provider.

**Voice Quality.** We compare voice quality of VoLTE and Hangouts. Since we are unable to capture VoLTE voice packets, which are handled within the hardware, we cannot apply traditional evaluation techniques of VoIP to conduct the comparison. We thus compare the recorded audio of the VoLTE and Hangouts calls. For the tested audio samples, we use four reference speech materials from ITU (International Telecommunication Union) recommendations. They include two male and two female American English speakers. Each consists of four simple, meaningful, and short sentences.

We do comparison study based on the subjective measurement method stipulated by ITU [12]. The subjective approach is used because the perception and evaluation of the voice performance is ultimately subject to users. The tests include both ACR (Absolute Category Rating) and CCR (Comparison Category Rating). ACR requires testers to give opinion scales from 1 to 5 on the quality of the audio they heard. In CCR tests, testers are presented with a pair of VoLTE and Hangouts audio files on each trial, and then give a score from -3 (much worse) to 3 (much better). The score, 0, denotes about the same. Note that the order of the pair audio files is randomly chosen for each trial.

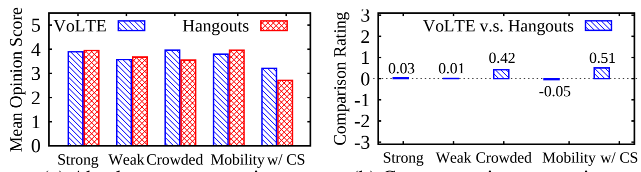
The audio is transmitted through the call from the sender phone, and recorded at the receiver phone. We prevent background noise from our recordings. The tested audio sample is played by a computer to the sender phone through a connected audio line. The audio received by the receiver phone is forwarded to a computer through another connected audio line, and then recorded by a software, called Audacity [13], in 16-bit, 44.1kHz format. We also keep the volume settings of all computers and phones identical for all the experiments.

We do three recordings for each of four tested samples in each scenario. We consider five scenarios: (1) both phones are in the strong-signal area, (2) both are in the weak-signal, (3) the receiver is in a crowded but strong-signal area, (4) the receiver is in mobility (crossing cells), and (5) the receiver is in the strong-signal area and the sender is a CS-based phone. Note that in latter three scenarios, the sender has strong signals. We recruit 50 university students to do subject measurement, and the experiment settings required by ITU [12] are as follows. The tests are conducted in a quiet room with around 90 $m^3$ by eligible listeners (*e.g.*, they have not participated in any subjective test during the recent six months). Each test takes around 35 minutes, so the listener's fatigue is considered negligible.




(a) Weak Signal (b) Strong Signal

**Figure 2: Call setup time (maximum, median, minimum) in weak-signal(a) and strong-signal(b) scenarios.**




(a) Absolute category rating (b) Category rating comparison

**Figure 3: Voice quality comparison between VoLTE and Hangouts (VoIP).**

Figure 3(left) shows the average ACR scores of VoLTE and Hangouts audio in the five scenarios. In Cases (1), (2) and (4), the differences between VoLTE and Hangouts in all the cases are below 0.2. They can be considered to be comparable. In both Cases (3) and (5), VoLTE performs better than Hangouts by about 0.4. It shows that the former's high-priority bearers are effective in the crowded area and its translating gateway for CS performs better. Figure 3(right) shows the average CCR scores by comparing VoLTE with Handouts. The results are similar to the ACR scores. Except Cases (3) and (5), they are comparable. Note that ITU recommends that both ACR and CCR should be considered for their average values.

Note that our finding that VoLTE and VoIP are comparable, is consistent with other studies. For example, NSN (Nokia Siemens Network) Smart Labs claimed that from their experimental results [14], VoLTE and VoIP applications achieved a pretty similar mean opinion score (MOS), which is a numerical indication of the users' perceived quality of received media after compression and/or transmission.

**Call Drop Rate.** We consider the call drop rate mainly in three cases. We first test the static case for 10 locations with strong/medium/weak signal strength. We test two mobility cases without and with inter-system switch (*e.g.*, 4G→2G/3G). Each mobility case has 10 different routes. Each location or route is tested with 20 2-minute calls.

It is observed that the call drop rates of VoLTE and VoIP are comparable. Both of them do not have any call drop in the static case. In the mobility case without inter-system switch, VoLTE does not drop any calls, whereas VoIP has small ratio of 0.5%. When an inter-system switch occurs, their call drop rates increase to 8% and 4%, respectively. VoLTE has a higher drop rate, rooted in its SRVCC. It proceeds an intricate cross-system/domain handoff. Specifically, a VoLTE call has to be migrated from a 4G packet-switched voice service to a 3G circuit-switched service (i.e., cross-system/domain handoff). However, the VoIP calls do not require to cross domains, but switch only between different PS systems, 4G PS and 3G PS. Its procedure is much less complex than that of crossing both systems and domains. The complex procedure results in higher failure rates of VoLTE.

# 4. VOLTE* DESIGN

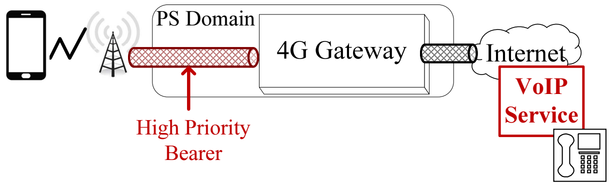



**Figure 4: VoLTE* overview.**

We now describe a new proposal, called VoLTE* (shown in Figure 4), which seeks to achieve the best of both worlds. VoLTE* uses the Internet VoIP scheme, but leverages the priority service offered by the LTE network infrastructure. We show that both LTE carriers and mobile users can benefit from this solution alternative. On one hand, it will serve the general public well for its lower cost and comparable quality to VoLTE, as well as more choices. On the other hand, operators also gain from the prioritized delivery in LTE networks.

Note that we are not championing to abandon VoLTE. VoLTE remains appealing to certain niche user groups who demand high-quality, guaranteed voice calls all the time (*e.g.*, police officers, company executives, medical emergency workers). The carriers with the VoLTE deployment can serve these kinds of demands. However, VoLTE* is proposed for the carriers which do not afford or are reluctant to spend the cost of the VoLTE deployment and maintenance.

## 4.1 VoLTE*: How it Works

VoLTE* supports four service classes of call services, as shown in Table 1. This is to exploit the diverse priority bearers offered by the LTE infrastructure. We retain two classes for VoLTE (*i.e.*, First class) and best-effort VoIP (*i.e.*, Economy class). Note that the first class offers the VoLTE-like call quality, but does not rely on the VoLTE deployment. The Business class always offers better service than Economy. Carriers may provide it using the bearer with the priority-level 7 [15], which is also assigned for voice. Both control and data planes can be carried at this priority level. Note that, this bearer has higher priority than that used for the Economy class (*i.e.*, 9), but has lower priority than those used for VoLTE control (*i.e.*, 1) and data (*i.e.*, 2) planes. Users of the Economy class thus pay less than that of the First class. The Deluxe Economy class provides users with adaptive VoIP service. A user is typically served as the Economy class, but will be adaptively upgraded to the Business class whenever needed (*e.g.*, too much resource is consumed by Economy users). This enables the user to receive call service better than Economy but worse than Business.

VoLTE* aims to put more functions into the user device and seeks for the network to provide only compact support for voice.

### *4.1.1 Functions at User Device*

The VoLTE* application is given privilege to manage the bearers by sending AT commands [16] to the hardware of user device. The AT commands are defined for the software to control network service access. They are commonly used in practice. For example, Android OS uses them to dial call and establish data connections through Radio Interface Layer (RIL). By AT commands, VoLTE* is capable of activating, modifying and deactivating its serving bearers.

### *4.1.2 Essential Support at Network*

In the network, four major supports are required. First, the network provides only differential pipe service, but does not manage them. It initially creates two VoIP bearers for signaling and voice.

| Service Class | Description |
|---|---|
| **First** | Akin to VoLTE |
| **Business** | Always better than best-effort |
| **Deluxe Economy** | Better than best-effort when needed |
| **Economy** | Best Effort |

**Table 1: Four service classes of VoLTE*.**

Afterwards, the differential priority services are configured upon the VoLTE* application's request. Second, the network leverages the existing VoIP services, so that it does not need to deploy the IMS core. To guarantee the performance of VoIP signaling/voice outside its network, carriers can rely on the IPX (Internetwork Packet Exchange).

Third, the detection of congestion occurrence needs to be supported for the Deluxe Economy class. It can be done by the existing LTE mechanism of packet delay budget (PDB) for the VoIP bearers. PDB defines an upper bound for the packet delay between the phone and the 4G gateway. When PDB is not met due to non-radio-quality issues (learned from the base station), the LTE network upgrades the VoIP bearer to Business class. Once the PDB of all Economy users in a cell is satisfied, the users will be downgraded back to the Economy class. Fourth, most VoIP service providers rely on peer-to-peer voice communication. Carriers can enable Mobile-to-Mobile communication for the voice session. If both VoLTE* ends belong to the same carrier network, they can exchange voice packets directly through the LTE network without reaching the Internet.

We want to note two things. First, the VoLTE* service can support the handover from 4G to 2G/3G systems without additional requirements on the network. The reason is that VoLTE* is a packet-switched service, which is supported by all of 2G/3G/4G systems. Therefore, the handover involves only an inter-system switch, which has been supported by most of mobile networks [17].However, the data rate of 2G/3G might not always satisfy the demand of VoLTE*; it varies with carriers or locations [18]. For example, the average upload/download rate in Sprint 3G is merely 0.6 Mbps / 1.2 Mbps, whereas the average upload/download rate in T-Mobile is 7.4 Mbps / 31 Mbps [18]. Second, VoLTE* can meet the common lawful requirements of mobile carriers, such as emergency calls, interception of suspicious calls, tracking of users' locations, etc. For the dialing of emergency calls, VoLTE* can leverage the Emergency Bearer Service procedure [17], which is stipulated by the standard, to establish a bearer for the emergent services. However, the other two requirements can also be supported by VoIP service providers or/and carriers. For example, Microsoft allows FBI to access its Skype system to intercept calls [19]and carriers can help VoIP service providers to track the VoLTE* users' locations by their IP addresses. Since VoLTE* users' IP addresses are assigned by carriers (4G:P-GW [20], 2G/3G:GGSN [20], or carriers' NAT servers), carriers can obtain the IMSIs (International Mobile Subscriber Identity) [21] of VoLTE* users by their IP addresses and discover their locations through the paging procedure using IMSIs [20, 22].

## 4.2 VoLTE* Benefits All Parties

We believe that mobile users, carriers, and VoIP service providers can all benefit from VoLTE*.

**Mobile Users: Better Services at Cheaper Fare.** Users benefit from VoLTE* in both lower charge and richer services (*e.g.*, video calls). First, the charge for call service can be cheaper. A survey [23] shows that an American user spends averagely around 450 minutes per month when talking over the phone. We compare the current 1-minute-call charge between typical cellular call ser-

| Charge (cent/min) | | T-Mobile | AT&T | Verizon | Sprint |
|---|---|---|---|---|---|
| Cellular Call | 450 mins | 6.7 | 8.9 | 7.8 | 6.7 |
| | 900 mins | 3.3 | 4.4 | 3.9 | 3.3 |
| Hangouts | 450/900 mins | 1.2 | 1.2 | 0.6 | 0.9 |

**Table 2: The charge comparison of cellular call and Hangouts call service from four major US carriers.**

vice and VoIP service (Hangouts is used) in four major US carriers based on the average usage (*i.e.*, 450 mins) and heavy usage (*i.e.*, 900 mins). For all the carriers, most plans have either unlimited call with an amount of data service or data service only. We thus consider the charge of call service based on the former plans with the smallest amount of data service, and then subtract the charge of the data service from their total price. The charge of the data services is based on the data plane with the most expensive data unit, *i.e.*, 1 GB data service only. We can then obtain the monthly price, from $30 to $40, and, from $10 to $20, for the unlimited call service only and 1 GB data service only, respectively.

The comparison results are given in Table 2. In Hangouts, the total volume of signaling and voice packets is around 0.6 MB (signaling takes 9.3% of traffic) per 1-minute call. Note that we consider the volume of signaling messages based on the average call duration of an American, 1.8 minutes [24]. For example, there are 250 calls with 450 minutes. We observe that the 1-minute-call charge for Hangout and cellular voice for normal users is ¢0.6-¢1.2 and ¢3.3-¢8.9 per minute, respectively. The 1-minute call charge for cellular voice service is $2.8-13.0$ times than that of Hangouts. It shows that users still benefit from VOLTE* of better voice quality even when carriers double the charge for the Business and Deluxe Economy service classes.

Second, multimedia call services are already provided by current VoIP service providers, whereas VoLTE mostly supports voice calls only to date. For example, Hangouts supports video call and multimedia content sharing (*e.g.*, slides) during a call, and such multimedia services are quite mature and stable already. In contrast, VoLTE is still at its early deployment stage with basic voice call service.

Note that not all consumers are willing to pay for the prioritized VoIP traffic. This is why we propose four different service classes of VoLTE*. If some consumers do not want to pay for it or are reluctant to pay too much, they can still have voice service with lower classes. Moreover, we believe that the service classes with traffic prioritization can still be cheaper than VoLTE, since VoLTE* does not require the high cost of IMS deployment.

**Carriers: Get More Revenue from Priority Delivery.** According to [23], mobile users spend less time on talking, while taking more time on text messaging and Internet access. Call services via VoLTE thus generate less revenue for operators over time. With VOLTE*, operators avoid deployment cost and maintenance of VoLTE, yet still providing their 4G users with comparable voice service. New revenue streams also come from the prioritized delivery service by the carrier network. Moreover, the offered services can be easily extended to other multimedia ones, such as video conference calls, with the help of current VoIP services.

**VoIP Service Providers: More Active Users.** For VoIP service providers, although they provide carriers with free voice service, they benefit from more *active* users who remain online more often when accessing VoIP services.

# 5. DISCUSSION

We here discuss both technical and non-technical drawbacks of VOLTE*. They may be the reasons why carriers will still keep VoLTE but not switch to VOLTE*, even if the high cost of IMS deployment is required.

**Technical Drawbacks.** VOLTE* does not support two major network features which are leveraged by VoLTE. First, VOLTE* does not support the VoLTE-like energy saving mechanism. VoLTE uses a fixed packetization interval, 20 ms, so that base stations can schedule voice packets delivery for better energy saving. However, the sizes of VoIP packets usually vary. Second, VOLTE* does not support the VoLTE-like coverage enhancement, where the Transmission Time Interval (TTI) bundling [25] is employed. It transmits duplicate VoLTE voice packets in consecutive time slots (up to 4) while users are at the cell edges. Based on the estimation of a report [26], it can improve uplink coverage by $2-4$ dB.

Moreover, VOLTE* requires carriers to spend efforts on developing a set of new interfaces, which are used by VoIP service providers to employ the mobile networks' high-priority bearers. It is because they have not been proposed in the literature or defined in the standard. Without prudent designs, they may make a security breach toward the core network, because they allow the network outsiders to manipulate the core network operations.

**Non-technical Drawbacks.** VOLTE* requires carriers to collaborate with VoIP service providers, but the sharing of both customers and the revenue may bring carriers some business concerns. We here present two examples, but the concerns are not limited to them. First, carriers may have risks of hurting their business by sharing customers. For example, the VoIP providers may do other commercial behaviors, which cannot be controlled by the carriers, to the customers, and they may cause customers' complaints. Moreover, it is difficult to resolve the sharing issues, if the collaboration of VoIP providers and carriers is terminated.

Second, it may be more difficult than usual for carriers to push new services. Once they rely on the VoIP providers to offer multimedia services, their plans would be impeded by the providers. In addition, they require to share the revenue of new services with the VoIP providers, and determine a new business model for each new service.

# 6. RELATED WORK

VoLTE has been actively investigated in industry (*e.g.*, [26–28]) and recently started to attract research attention [29–33]. Most efforts focus on its performance measurement [26, 27, 30] or deployment planning to improve performance [29]; Several recent efforts investigate VoLTE security [28, 31–33]. In particular, Jia *et al.* reveals that the early deployment of VoLTE in US suffers various performance problems [30] while mobile network industry advocates VoLTE with better or comparable voice quality [26,27]. Our recent work and Kim *et al.* uncover that the VoLTE deployment is vulnerable to many attacks, including free data access, over-billing, denial of data service, voice mute and energy drain [31–33]. This is partly due to imprudent implementation at the early phase, partly due to complexity and substantial changes to the existing LTE architecture caused by VoLTE support. This also motivates us to revisit the current VoLTE solution and devise an alternative solution.

Recent years witness other LTE voice solutions: circuit-switched fallback (CSFB), single radio voice call continuity (SRVCC), simultaneous voice and LTE (SVLTE). CSFB migrates 4G LTE users to 3G/2G networks and leverages their legacy CS domain to support voices call [34]; Our previous studies reveal its performance issues and security implication (potential harm to normal data services) [32, 35]. SRVCC complements VoLTE and hands over VoLTE voice calls to 2G/3G networks in case of no LTE coverage [11]; SVLTE supports data in 4G LTE and voice in 3G/2G CS at the same time but it requires dual radio interfaces [36]. All are interim solutions since they require non-LTE networks (3G/2G networks). In this work, we focus on the voice solution that uses LTE only.

# 7. FUTURE WORK

In order to promote VoLTE*, we plan to pursue the following two items in our future work.

**An Automated Tool for Large-scale Experiments.** For the large-scale experiments of the comparison between VoLTE and VoIP applications, we seek to develop an automated tool of trace collection and release it to normal users. It will collect the traces which are required for three performance metrics of call performance: call setup time, call drop rate and voice quality. To measure the former two metrics, the tool will record the signaling messages of call setup, call accept, and call failure. To gauge the voice quality, it will log the voice packets of both VoLTE and VoIP applications, and apply the evaluation techniques of VoIP performance.

**Promoting VoLTE* to the Industry.** We plan to promote VoLTE* to not only the carriers which have not deployed VoLTE, but also the 5G standardization groups. First, we will seek the opportunities to collaborate with any carriers to deploy VoLTE*. We can learn whether there are any more practical issues, and then address them. We can further gain the lessons of how the Internet service providers and carriers collaborate to offer services, which can be applied to the future mobile Internet services. Second, we will actively participate in the standardization process of 5G to promote VoLTE*.

# 8. CONCLUSION

Bearing the telecom-based design mindset, VoLTE calls for substantial upgrades on the infrastructure side (complex functions in the core), and device updates as well. In this work, we offer an assessment on whether it warrants the effort to deploy VoLTE or not. Our criteria are based on its deployment cost and operation complexity, as well as the benefits offered to different parties. It is unfortunate, that our answer seems to be negative. Though VoLTE remains appealing to those niche groups of users who demand high-quality, high-reliability, guaranteed calls all the time, it is not necessary to be so complex.

The lesson we learned is that VoLTE leverages the higher priority services (compared with the low-priority, best-effort delivery) in mobile networks to ensure quality calls. The priority services are provided by the LTE network, but not from the IMS subsystem. The VoLTE implementation thus does not require the deployment of IMS, a main roadblock for its fast rollout. As the device becomes more powerful over time, it is prudent to place more intelligence at the device rather than the network. It soulds obvious to the Internet community, but not to the mobile networking camp in practice.

# Acknowledgements

We would like to thank Dr. Kurtis Heimerl and the anonymous reviewers for their valuable comments. This work is supported in part by the National Science Foundation under Grants No. CNS-1421933, CNS-1422835, CNS-1528122 and CNS-1527613. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

# 9. REFERENCES

[1] Voice over LTE. http://www.gsma.com/technicalprojects/volte.
[2] 3GPP. TS23.228: IP Multimedia Subsystem (IMS);Stage 2, 2014.
[3] MetroPCS, SK Telecom, LG Uplus Claim VoLTE First, 2012. http://www.telecomengine.com/article/metropcs-sk-telecom-lg-uplus-claim-volte-firsts.
[4] Volte market revenue share of 12% to be held by video calling and supplementary services in 2020, Oct 2015. http://www.prnewswire.com/news-releases/volte-market-revenue-share-of-12-to-be-held-by-video-calling-and-supplementary-services-in-2020-530219051.html.
[5] AT&T: 2015 will be the year of mass market VoLTE. http://www.fiercewireless.com.
[6] VoLTE gears up for mass market. http://www.telecomasia.net.
[7] Ericsson: Volte deployment delays not surprising due to network complications, 2014. http://www.fiercewireless.com.
[8] RFC3261: SIP: Session Initiation Protocol, June 2002.
[9] RFC 3550: RTP: A Transport Protocol for Real-Time Applications, Jul 2003.
[10] 3GPP. Operation, Adminstration, Maintenance (OAM).
[11] 3GPP. TS 23.216: Single Radio Voice Call Continuity (SRVCC), March 2011.
[12] P.800: Methods for subjective determination of transmission quality.
[13] Audacity. http://audacity.sourceforge.net/.
[14] Is volte better than ott voip for carriers and customers. http://pressanykey.co.nz/wordpress/volte-better-ott-voip-carriers-customers/.
[15] 3GPP. TS23.203: Policy and Charging Control Architecture, 2013.
[16] 3GPP. TS27.007: AT command set for User Equipment (UE), 2011.
[17] 3GPP. TS23.401: GPRS Enhancements for E-UTRAN Access, 2011.
[18] P. Magazine. http://www.pcmag.com/article2/0,2817,2485838,00.asp, 2015.
[19] Microsoft allows nsa/fbi to access outlook, skype, other communication software. http://www.webpronews.com/microsoft-allows-nsafbi-to-access-outlook-skype-other-communication-software-2013-07/.
[20] 3GPP. TS23.060: GPRS; Service description; Stage 2, 2006.
[21] H. Holma and A. Toskala. *WCDMA for UMTS: HSPA Evolution and LTE*. John Wiley & Sons, Inc., New York, NY, USA, 2007.
[22] 3GPP. TS24.301: Non-Access-Stratum (NAS) protocol for Evolved Packet System (EPS); Stage 3, Jun. 2013.
[23] Experian: Americans spend 58 minutes a day on their smartphones. http://www.experian.com.
[24] Average Local Mobile Wireless Call Length in the United States from 1987 to 2012. http://www.statista.com.
[25] 3GPP. TR36.824: LTE coverage enhancements, 2012.
[26] N. Networks. From Voice over IP to Voice over LTE, 2013. http://tinyurl.com/q79vyu6.
[27] Qualcomm. The Voice Evolution, 2012. http://tinyurl.com/q5pe99h.
[28] VoLTE: Progress and Problems, April 2014. http://www.rcrwireless.com/article/20140416/networks/volte-progress-problems/.
[29] A. P. S. Louvros and A. Gkioni. Voice Over LTE (VoLTE): Service Implementation and Cell Planning Perspective. In *System-Level Design Methodologies for Telecommunication*, pages 43–62. Springer, 2014.
[30] Y. J. Jia, Q. A. Chen, Z. M. Mao, J. Hui, K. Sontinei, A. Yoon, S. Kwong, and K. Lau. Performance characterization and call reliability diagnosis support for voice over lte. In *MobiCom*, 2015.
[31] C.-Y. Li, G.-H. Tu, C. Peng, Z. Yuan, Y. Li, S. Lu, and X. Wang. Insecurity of voice solution volte in lte mobile networks. In *CCS*, 2015.
[32] G.-H. Tu, C.-Y. Li, C. Peng, and S. Lu. How Voice Call Technology Poses Security Threats in 4G LTE Networks. In *IEEE Conference on Communications and Network Security (CNS)*, September 2015.
[33] H. Kim, D. Kim, M. Kwon, H. Han, Y. Jang, D. Han, T. Kim, and Y. Kim. Breaking and fixing volte: Exploiting hidden data channels and mis-implementations. In *CCS*, 2015.
[34] 3GPP. TS23.272: Circuit Switched (CS) fallback in Evolved Packet System (EPS).
[35] G. Tu, C. Peng, H. Wang, C. Li, and S. Lu. How Voice Calls Affect Data in Operational LTE Networks. In *MobiCom*, Oct. 2013.
[36] Sonlte. Notes on Simultaneous Voice and LTE (SVLTE).