Toward 5G: When Explosive Bursts Meet Soft Cloud

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Abstract

Rapid growing demand for mobile data traffic challenges capacities and service provision in the next-generation (5G) cellular networks. Real measurement data from operating cellular networks indicates that the traffic models and scenarios disobey our traditional assumptions (i.e., expressing bursty nature). As a result, current network architectures and service management may cause experience deterioration of subscribers in future networks. In this article, we propose three approaches to alleviate the influence of various traffic bursts: baseband resource pool on a cloud platform as wireless infrastructure to enhance the capacity and flexibility of networks, cloud core networks to provide dynamic extension and service flow control abilities, and software-defined bearer networks to simplify service delivery instructed by core networks. Different from conventional stovepipe-like cloud computing network architectures, our proposed architecture interconnects and shares information between entities, breaking through horizontal device barriers and vertical layers. These cloud-based approaches not only avoid the potentially negative impact of bursts, but also provide a software-controlled end-to-end service management framework for future cellular networks. In addition, by taking advantage of open interfaces of cloud-based network elements, service control algorithms and network APIs could also be implemented to realize smart and soft 5G cellular networks.

To cope with various emerging service demands and application innovations, many promising service and application scenarios of fifth generation (5G) cellular networks have sprung up. Notable examples include dense small cells, non-Third Generation Partnership Project (3GPP) access convergence, machine-to-machine (M2M) communication, e-health, online to offline (O2O), self-driving cars, and so on. As a result, more base stations (BSs) have to be deployed by operators to provide enough data access as well as self-deployed small cells. However, with conventional network planning methodologies, the capacity increase of BSs still lags behind the explosion trend of traffic demands, thus leading to many challenges. Targeting at the next-generation cellular networks (i.e., 5G), one of the main challenges for operators is the surprising boom of over-the-top (OTT) applications around the world recently. In particular, an OTT service sends keep-alive messages to their servers periodically, and may generate huge unexpected bursting traffic according to some social events like group chatting and rush purchasing. Consequently, they make the network congested, even temporarily unavailable in some extreme situations [1]. Besides, the second challenge is the universal adoption of M2M devices with new traffic characteristics. These emerging characteristics, like always online, massive connected, high uplink volume and timer-triggering activities, are quite different from those of human beings. When millions of M2M nodes get access to the networks and are activated simultaneously via thousands of BSs, the core networks may be congested due to the unexpected traffic burst. Moreover, in order to enhance indoor coverage and offload explosive cellular traffic, gardened 3GPP cellular networks have become slightly open by allowing customers to deploy small cells individually and granting wireless access points (APs) to access the legacy infrastructure [2]. These smalls cells and APs significantly boost the on-demand network capacity provision, but they are beyond the reach of operators and switching on/off them would incur frequent updates of the network topology. In other words, another challenge comes as the coordination and handover between cells requires timely information sharing via back-haul, hence the frequent establishment and deletion of links also challenge the flexibility of bearer networks. The bursts within wireless access, core networks and topology give rise to the non-negligible challenges of 5G cellular networks.

Until now, infrastructures of cloud computing have been quickly adopted in various networks to meet the dynamic computing demands. Meanwhile, cellular networks are also changing themselves, evolving from closed systems to open and soft forms. On the other hand, software-defined networks

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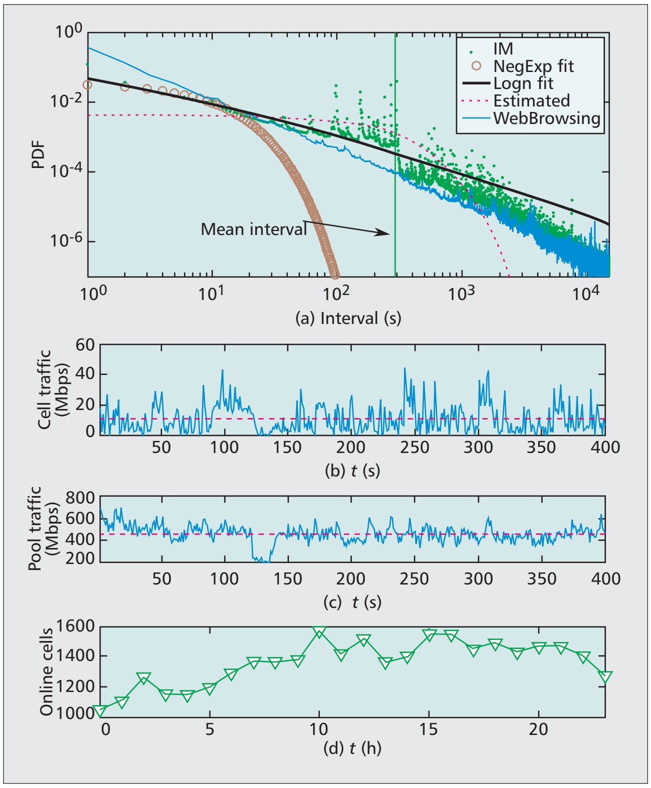

Figure 1. a) Inter-arrival time of services (IM and web browsing); b) cell traffic variation in NodeB; c) aggregated cells (pool) traffic variation in RNC; d) online number of self-deployed small cells.

(SDNs) have been deployed in core networks to adapt service flows to the dynamic networking environment. SDN architecture decouples network control and forwarding functions, thereby allowing network administrators to implement service-oriented policies via the flexible open interfaces. However, due to the complex protocols of 3GPP-based cellular networks, the necessary abstractions are more difficult than their counterparts in the backbone IP networks. Fortunately, cloud infrastructure can decouple the hardware and software of the network elements, while control functions of SDNs can be embedded into the software of network elements, thus making SDN-based cellular networks feasible.

In this article, we first investigate the representative scenarios that cause the overloaded bursts within cellular networks: wireless service bursts on air interface, non-access stratum (NAS) signaling storms in core networks, and frequent topology updating in bearer networks and backhauls. Second, SDN-enhanced cloud infrastructure designed for future cellular networks is introduced and employed to address the burst problems, as well as innovate service management. Finally, benefiting from this new architecture featuring soft and cloud advantages, service flow control mechanisms with wireless feedback and network application programming interfaces (APIs) are proposed to achieve demand-driven, resilient, and efficient 5G cellular networks.

Bursts of Cellular Networks

Nowadays, diverse rising mobile applications have created various new service demands in our daily lives and generated many unexpected traffic characteristics that greatly impact the performance of the cellular networks. These newly emerged traffic characteristics may shed light on how to design the next-generation cellular networks.

In order to grasp the fundamentals of various emerging traffic patterns, we have collected three months' anonymous traffic records of various kinds of networks (GSM, UMTS, and Long Term Evolution, LTE), which were generated from 7 million subscribers and served by about 20,000 BSs of China Mobile within a region of 3000 km^2. Accordingly, Table 1 summarizes the main differences in the statistical distributions of traffic patterns between our experimental results and the conventional 3GPP models in [3], while Fig. 1a particularly illustrates the inter-arrival time measurements of web browsing and instant messaging (IM) of mobile users, and the corresponding statistical fitting results. By fitting the empirical data, the lognormal distribution is observed to best fit the inter-arrival time of IM service, while the power-law (Pareto) distribution fits the inter-arrival time of web browsing service best. Notably, the peaks in the probability density function (PDF) of inter-arrival time of IM service (i.e., green dots in Fig. 1a) are caused by keep-alive messages, which are periodically sent to servers to keep mobile users notified in a timely manner when a message is received. This keep-alive mechanism is widely adopted by most IM and social network service (SNS) applications [4]. It would consume a large percentage of BS resources with the content-less messages and potentially have a seriously negative impact on other delay-sensitive services.

Table 1 and Fig. 1 also provide an interesting observation that the distributions of inter-arrival time of web browsing and IM are not exponential, as widely assumed [3], but heavy-tailed, which clearly reflects the bursty characteristics in the traffic's time domain [4]. In other words, mobile users would generate a large amount of service demands in a short time but be silent for a long time. Specifically, Figs. 1b and 1c depict the traffic volume over the Iu interface of a NodeB and a radio network controller (RNC) in busy time, the peak-to-average ratio (PAR) of which is 4.15 and 1.51, respectively. Furthermore, most cellular traffic models such as [3] generally assume the inter-arrival time and service time to be independent of other sessions or messages. However, based on the real measurements [4], we find that the traffic of IM service exhibits long-range dependence (LRD) attribute, which exerts the dependence property between messages. The impacts of heavy-tailed LRD traffic in wired networks have been investigated and already expressed significant influence on network management [5]. When we design and optimize cellular networks according to the conventional method, traffic volumes in peak hours are taken into account to determine the maximum capacity. This kind of estimation method is widely implemented and proven effective in circuit-switched (CS) and early packet-switched (PS) services. According to Fig. 1a, the mean inter-arrival time from our measurements is about 292 s, as marked by the vertical green line, while the corresponding exponential distribution estimated by the same mean inter-arrival time is plotted as a red dotted line. Therefore, if we design the cellular networks by assuming the inter-arrival time distributed exponentially, BSs would be instantaneously overloaded by the underestimated bursty traffic, particularly in busy public areas (hot spots).

For traffic measurements of typical M2M services, the message inter-arrival time and message length are constant, which is also different from human behavior patterns and usage. In many cases, the interactions between M2M devices and platform are triggered by timers or events, so M2M devices are likely to generate numerous messages simultaneously. It is not difficult for each BS to handle concurrent service requests from hundreds of M2M devices even in 2G mode. However, when core networks serve hundreds of thousands of M2M devices together, which simultaneously initiate

Parameter	3GPP model	Measurement results
Web browsing session inter-arrival time	NegExp1	Power-law
Web browsing session length	Geometric	Power-law
IM message inter-arrival time	NegExp	Lognormal
IM message length	Geometric	Power-law
IM keep-alive period	Constants	Discrete constants
M2M message inter-arrival time	Not mentioned	Discrete constants (partial)
M2M message length	Not mentioned	Discrete constants (partial)

Table 1. Model differences of distributions.

signaling procedures like authentication and bearer activation, traffic bursts bring about a signaling storm and may crash the core networks. Generally, these signaling procedures interact in the NAS layer of 3GPP protocols, such as attach/detach, bearer activation, location update, and authentication, so we call them NAS signaling storms. For example, if a power failure of an area takes place but is recovered later, M2M devices without uninterrupted power supply (UPS) in this area would attach to the network simultaneously, causing the storm in core networks being far beyond operators' expectation. Another example is the M2M system attacking by hackers or misoperation, the fixed capacity of core networks would also be overflowed by a flood of NAS signaling messages. Figure 2 illustrates the variation features of bearer activation success rates from a real power recovery case on the S1 interface of core networks, when a signaling storm takes place within the evolved packet core (EPC) caused by a simultaneously reset operation of millions of M2M devices. We observe that the maximal handling capability of the mobility management entity (MME) is about 80,000 requests in 5 min, and the performance and capability seriously deteriorate when the signaling storm bursts. Moreover, the handling capability of MME is not the only bottleneck by the signaling storm, links between the home subscriber server (HSS) and MME are also congested because of the overwhelming authentication messages.

The ever growing data explosion in mobile devices puts a heavy strain on cellular networks. Operators are attempting to address this challenge by offloading traffic to self-deployed small cells and APs. Meanwhile, in 3GPP TS 23.261, the access network discovery and selection function (ANDSF) framework was introduced to enhance flow offloading agility and conduct more specific traffic identification. Taking advantage of policies that can be executed on different services, cells, plans, and time, operators could intelligently determine the kind of service traffic to be offloaded and the potential destination networks. Figure 1d shows the variation features of online small cells deployed by users themselves within a city during one day, while frequent switching on/off of small cells are out of an operator's control. Indeed, each switching on/off of small cells involves significant configuration procedures within both backhauls and bearer networks. For example, when a home eNodeB (HeNB) is online, links with neighboring BSs will be immediately established as X2 interfaces, and the links need to promptly be deleted when this HeNB is switched off. When a mobile terminal changes its access network from cellular to WLAN, data flows are managed by ANDSF to realize traffic offloading; meanwhile, the authentication center is changed from the HSS to an authentication/ accounting/ authorization (AAA) server. Moreover, data traffic in different access networks encounter different policies: web pages with WLAN access may be inserted with advertisements to bring additional income, while cellular access can coordinate with the content cache in the service gateway to reduce the load of backhauls. As a result, the traffic offloading operation not only challenges the stability of backhauls and bearer networks, but also adds further complication to service delivery by operators.

In a nutshell, Table 2 summarizes all the possible bursts in future cellular networks, which are addressed in the following sections.

When Explosive Bursts Meet Soft Cloud

To meet the challenge of bursts, it is necessary for mobile operators to deploy many more BSs. However, our real traffic measurements show that signaling storm of NAS layer may happen less than one time per month. According to another real wideband code-division multiple access (WCDMA) network traffic measurement in a major European city, 90 percent of cell congestion durations are shorter than 1.2 s, and 90 percent of cell congestion separation times are below 780 s [6]. Therefore, operators should carefully consider the trade-off between cost and capacity expansion to meet the bursty demands. In order to alleviate the negative impact of bursts in 5G cellular networks, we propose cloud-based network architectures and SDN solutions, as illustrated in Fig. 3.

Recently, a substantial body of initiatives has been prompted toward cloud cellular network architectures, such as C-RAN of China Mobile, Liquid Radio and Liquid Core from NSN, Light Radio from Alcatel-Lucent, CloudRAN and CloudEPC from Huawei, and Cloud Radio and Cloud UniCore from ZTE [7]. One of the similarities in these architectures is that the network elements are implemented on the cloud computing platform, which allows flexible sharing of the capacity wherever it is needed, thus solving the network resources underutilization issue caused by temporal-spatial traffic fluctuations [8]. However, cloud-based network elements work as separate entities in an independent manner; therefore, advantages like open interface and interconnection features may not play a constructive role currently. Meanwhile, SDN realization in mobile cellular networks emerges as well, such as OpenRadio from Stanford University, LTEHaul from Huawei, Mobile SDN from Juniper, and CellSDN from Alcatel-Lucent [9]. Nevertheless, the application of SDNs in cellular networks is still inconclusive and embryonic; even the working layer and service recipients remain vague.

Fortunately, both academia and industry have come to a consensus to leverage the merits from cloud computing and network function virtualization (NFV) in cellular networks in order to realize the telecommunications industry similar to the IT industry in recent years. In 2010, the International Telecommunication Union Telecommuncation Standards Sector (ITU-T) Focus Group on Cloud Computing (FG Cloud) was established to support services of cloud computing within telecommunication networks. Followed by ITU-T Study Group (SG) 13, detailed requirements and functional architectures of the cloud computing ecosystem are studied, covering inter- and intra-cloud computing technologies [10]. The

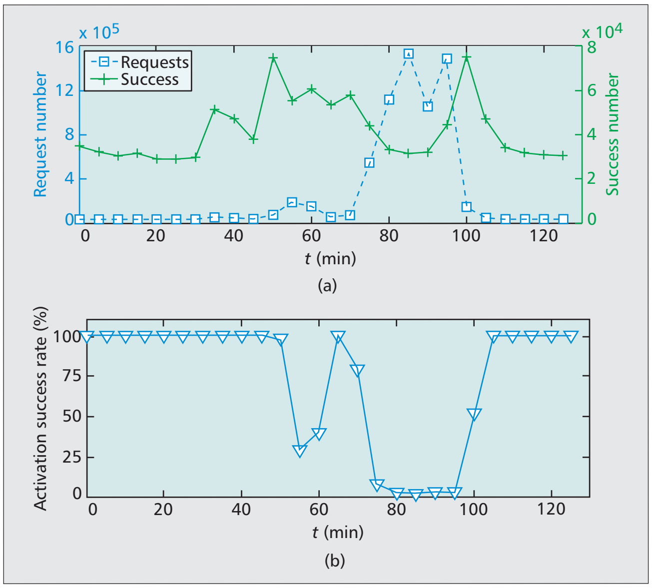

Figure 2. The impact of a signaling storm of the NAS layer on EPC: a) activation requests and successful activations during a signaling storm; b) activation success rate during a signaling storm.

Internet Engineering Task Force (IETF) also initiated a work group on cloud operations in 2010 to standardize the resource modeling and management in cloud computing. Also, a specification group of the European Telecommunications Standards Institute (ETSI) was set up to work on the technical challenges of NFV [11].

Basically, NFV, cloud computing, and SDN have something in common but are not the same concept. NFV focuses on migrating the entities of network elements onto a generalized platform and operation system, while cloud computing refers to the concept that the delivery of computing resource is a service with dynamic extensions. NFV and cloud computing concentrate on functions of devices to form a new method of operation and maintenance, but SDN focuses on inter-device functions to provide more flexible services. The upper left of Fig. 3 depicts the architecture of the cloud radio access network (RAN), which consists of distributed remote radio heads (RRHs), a general-purpose processor platform, a real-time operating system, and baseband software with open interfaces. After the distributed baseband processing units (BBUs) are migrated to the centralized baseband resource pool within the cloud, the network traffic curve would change from Fig. 1b to Fig. 1c, being less fluctuating. Therefore, benefiting from the diminishing size and easier deployment of BSs, the unbalanced spatial traffic distributions and short time-span bursts could be handled by sufficient computation resources on the cloud platform and ubiquitous RRHs. Besides, considering the low spectrum efficiency of GSM and UMTS, spectrum refarming is adopted by many operators to implement newer access technology on the spectrum of earlier technologies. Software of latest technologies like LTE-A could be loaded into a BBU pool to implement the spectrum refarming conveniently, without any new deployment or hardware update of BSs.

The right upper part of Fig. 3 illustrates the cloud EPC with SDN controllers. Except the data plane of the serving gateway (SGW) and packet data network gateway (PGW), most network elements of EPC are migrated into the cloud. The control plane of the SGW manages user equipment (UE) contexts, routing rules, and quality of service (QoS) control, while the control plane of PGW assigns IP addresses of UEs, and manages service sessions and charging. The data plane of the SGW acknowledges the commands from its control plane via an SDN controller, and the data plane of the PGW is integrated into SDN switches. Moreover, based on the cloud platform, the network elements turn into network functions and interconnect with each other, breaking through horizontal device barriers and vertical layers. When a NAS signaling storm happens, bottlenecks occur in both computation resources and signaling links between network elements. Therefore, the feature of dynamic extension of cloud computing is suitable for allocating more computation resources at once, and NFV could contribute to signaling link expansion using its internal bus. As a result, the influence from the bursts induced by simultaneous M2M device activities could be alleviated.

In Fig. 3, SDN switches converge the backhauls of thousands of BSs and APs, and follow the instructions from SDN controllers of EPC. For the framework in Fig. 3, once a self-deployed cell is online and the corresponding EPC is notified, X2 links, service routes, and offloading rules will be established in SDN switches according to SDN controllers. In cloud EPC, service signaling traffic is forwarded to different network elements according to the load of devices, and the attributes of BSs and subscribers. Therefore, we can allocate cloud resources as service-specific network elements to realize service separation, like EPC dedicated to M2M services. We can also benefit from the advantages of SDN like data monetization and local breakout to enterprise networks in order to make flexible services and plans according to attributes of areas and subscribers. Therefore, we could carry out service delivery demands by just adding forwarding and charging rules in SDN controllers, avoiding complex and multiple-point configurations. In this regard, the topology update could be more easily realized.

Surely it is worthwhile to notice the challenges to realize such cloud technologies in 5G cellular networks. For example, the key requirements of addressing the traffic burst issues are real-time dynamic extension and processing efficiency. When traffic bursts break out from massive devices, the cloud computing platform must be able to realize virtual computing resource expansion by monitoring the performance. On the other hand, the dedicated hardware and software of traditional telecommunications devices have been elaborately designed to achieve the highest efficiency. However, the general-purpose processor platform and operating system are not fully

Burst names	Generated by	Impacted objects	Burst cause
Wireless bursts	Smart phones	BSs	OTT applications and user behaviors
NAS signaling storm	M2M devices	HSS, MME, etc.	Simultaneous attaches and service requests
Topology updating	Small cells and APs	Backhaul and bearer networks	Popularity of self-deployed cells

Table 2. Summary of possible bursts in next-generation cellular networks.

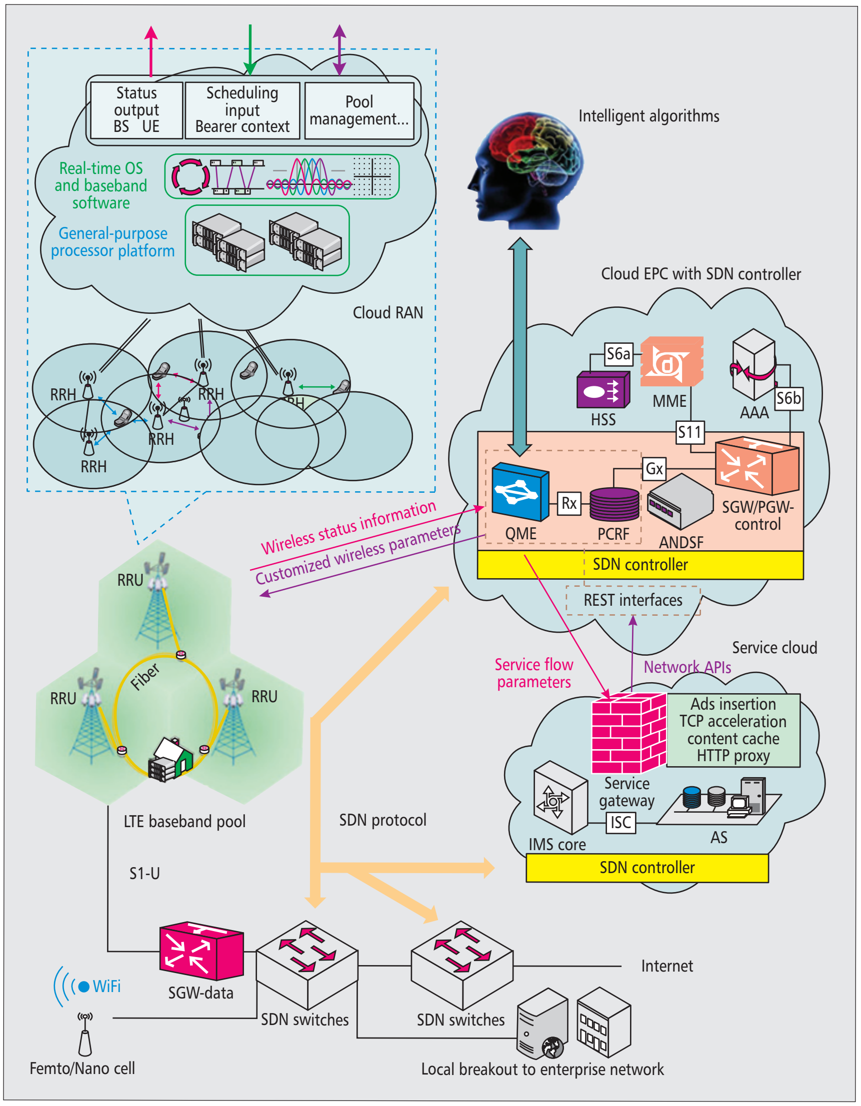

Figure 3. Realization of software-defined cellular networks based on cloud architectures.

matched with the computation model of the algorithms in cellular networks. A specific accelerator has also been required to enhance the efficiency of the cloud platform. In other words, the trade-offs between general and specific components of cloud-based cellular networks should be balanced. As a conclusion of this part, Table 3 summarizes the functions and applications of these cloud technologies, as well as the challenges in tackling the burst problems.

From Soft toward Smart: The Road Ahead

Recently, policy control and charging (PCC) [13] architecture has been deployed by many operators to meet QoS requirements. However, due to the one-way control mechanism without feedback information of the PCC architecture, networks determine the QoS policies only by static configuration of services and subscribers' profiles. Therefore, as shown in Fig. 3, we propose to deploy a novel QoS management element (QME) in a cloud EPC to get the real-time feedback from a cloud RAN, thus being capable of adjusting the QoS class identifier (QCI) as well as service flow parameters in the SGW dynamically. Different from conventional QoS management approaches, the proposed QME mainly focus on inter-device and inter-layer QoS optimizations. The QME could be integrated with either a policy and charging rules function (PCRF) or SGW to realize end-to-end service management, and interacts with the PCRF via an Rx interface.

There are two additional advantages from the cloud RAN as well:

- Real-time wireless information feedback on the user level becomes possible.
- Wireless parameters of scheduling strategies could be customized via external interfaces conveniently.

The red arrows in Fig. 3 specifically show that the wireless information (e.g., channel quality indication, reference signal received quality, resource block utilization) could be sent by the baseband resource pool, and the purple arrows express the referenced scheduling strategies sending to the cloud RAN. Therefore, compared to the present case where wireless information is invisible to upper layers in core networks, the cloud RAN and the corresponding baseband resource pool enables wireless information extraction and could contribute to more effective service flow management.

According to the wireless information exported from the cloud RAN, we can execute intelligent service control on QME. Generally, TCP parameters have been tuned to perform well in wired networks by controlling the transmission bit rate and delay when packet losses occur mostly because of network congestion. However, cellular networks also suffer from the delay problem due to fast fading and handoffs, while the TCP mechanism responds to all exceptions by universally invoking the congestion control and avoidance algorithms, resulting in end-to-end performance degradation. Many researchers have discussed various solutions such as proxy-TCP and medium access control (MAC) information sharing, but still did not take into account the viewpoints of wireless information and service-distinguished QoS management through cognitive learning and decision making processes [14, 15]. Specifically, transmission windows and forward delay of TCP in the gateway could be dynamically set to meet the different service requirements.

In order to spur more service innovations within 5G cellular networks, network capability could be opened to service providers and application developers. The concept on network API is proposed to facilitate developers to manage their services. Through an interface on QME, we can set up advanced network functions like: traffic offloading, QCI assignment of service flow, customized scheduling strategies, fine localization based on measurement reports, notification push, and even keep-alive messaging.

No doubt, there is still a long way ahead to build a smart QME to allocate network resources and manage services intelligently. First, OTT services hold private protocols of their applications and may change them without informing operators, so the learning processes and recognition rules of OTT services should be kept up to date. Second, the functions of network APIs need to be deliberately designed after taking into account the potential security influence on the commer-

Scenario	Key functions	Applications	Challenges
Cloud RA	Enhance processing capacity, cell coordination [12]	Resource and energy saving, spectrum refarming	Compromise between general and specific processors
Cloud EPC	Rapid resource extension	Service flow control	Embed EPC functions into SDN controller
SDN	Integration of access and service	Self-organized network, WLAN-offloading, local breakout to enterprise networks	Single-point management

Table 3. Summary of cloud applications in cellular networks.

cial cellular networks. Third, the huge amount of wireless information output from the cloud RAN requires high-level capability of dealing with the big data so that the in-memory data processing is capable of satisfying the demand of real-time analysis.

Conclusions

With the global popularity of mobile Internet, explosive bursts will be one of the key challenges of next-generation cellular networks. Many researchers have put forward the 5G goals aiming at higher capacity and speed; however, we deem a 5G cellular network as a flexible service-oriented ecosystem. Traditional stovepipe-like cellular networks with static resource management demonstrate poor performance and lack the essential flexibility. Therefore, we envision a software-defined cellular network based on an interconnected cloud computing platform with open interfaces, and expect it to achieve unified intelligent management across the RAN, core networks, bearer networks, and service platforms. Based on this open and elastic 5G ecosystem, wireless technology evolutions, convergence of 3GPP and IEEE 802 protocols, and application service innovations could be conveniently developed to realize a flourishing 5G era.

Acknowledgment

This article is supported by the National Basic Research Program of China (973Green, No. 2012CB316000), the Key (Key grant) Project of Chinese Ministry of Education (No. 313053), the Key Technologies R&D Program of China (No. 2012BAH75F01), and the grant of "Investing for the Future" program of France ANR to the CominLabs Excellence Laboratory (ANR-10-LABX-07-01).

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