Software Defined Networking in Next Generation Mobile Backhauls: A Survey

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***Abstract*—Decoupling the control and data planes has become synonymous with Software Defined Networking (SDN). This paradigm introduces a multitude of benefits to modern networks – such include reduction of management complexity and cost, modularity, optimized utilization, and isolated innovation. Due to the strict latency requirements of next generation mobile networks, it is widely accepted that decoupling these planes is key. The sheer volume of traffic that must be supported has driven the need for researchers to turn their focus to the mobile backhaul. This paper identifies the challenges faced by next generation mobile networks and investigates state-of-the-art solutions implementing SDN at the backhaul level. In addition, it presents five distinct categories of SDN-enabled solutions: mobility management, joint Radio Access Network (RAN) intelligence, multi-tenancy, caching, and traffic monitoring.**

***Index Terms*—3GPP, SDN, NFV, OpenFlow, 5G, Backhaul**

I. Introduction

The 3rd Generation Partnership Project (3GPP)'s Long Term Evolution (LTE) has been a major technology enabler in the mobile industry since its conception. Research in several disciplines had re-imagined the architecture of mobile networks, such as modulation schemes, spatial processing (such as MIMO), and Inter-Cell Interference Coordination (ICIC) [1]. With this shift, 4G LTE networks have been able to deliver higher throughput and less latency to even more users compared to its predecessor, 3G.

Expected to formally roll out in the fourth quarter of 2020, implementing 5G networks also pose a slew of challenges. Vertical markets such as the smart grids [2], vehicular networks [3], and even health care [4] impose ambitious performance requirements related to latency, reliability, and security [5]. Given these emerging use cases, and the ubiquity of mobile handsets, it is projected that the number of connected devices will rise between tenfold to one hundredfold accounting for one thousand times more data [6].

Ultra Dense Networks (UDNs) utilizing millimeter-wave bands and Cloud Radio Access Network (C-RAN) have been considered. UDNs are heterogeneous networks consisting of small (pico to femto) cells alongside existing macro cells. The addition of small cells allows for increased frequency reuse, amounting to high spectral efficiency and low up/downlink power consumption [7]. The logistics of adding more cells is handled by C-RAN [8] where baseband resources are pooled together in the BaseBand Unit (BBU), allowing for statistical multiplexing to further bolster efficiency.

As solutions have been proposed at the RAN level to support increasing numbers of connected devices and their diverse data requirements, another hurdle lies in aggregating vast amounts of traffic from the RAN to the core network. This infrastructure makes up what is known as the *backhaul* of the network. It is important for this architecture to also be part of the evolution.

This paper focuses on Software Defined Networking (SDN) enabled solutions that seek to alleviate stress from the backhaul and address other deficiencies towards future releases of 4G LTE as well as next generation networks, i.e 5G. It is accepted that separating the control and data planes will be essential for 5G [6], [9], [10], [11]. Key challenges and shortcomings of implementing SDN are also to be investigated.

The remainder of this paper is organized as follows: the next section discusses related work in this field and the novelty of this work. Sections III and IV provide an overview on the architecture of LTE networks and SDN, respectively. This is followed by a survey on the latest research in this field. Finally conclusions about the surveyed work will be drawn.

II. Related Work

Mobile networks [1], [8], [12] and SDN [13], [14] have been greatly considered separately in surveys. The benefits SDN has to offer towards meeting 5G's stringent requirements has led these topics to be explored in tandem by many researchers. For example, Nguyen *et al.* [15] investigate the advantages of leveraging SDN and Network Function Virtualization (NFV) in mobile networks. They note architecture, vague definitions of south and northbound interfaces, control plane scalability, and lack of evaluation tools as key challenges to SDN/NFV deployment in next generation networks.

Jaber *et al.* [6] have considered research strictly on mobile backhaul technologies. They have identified six major research areas which are highly active with regards to the backhaul: fibre-based, wireless, SDN enabled, cache enabled, green efforts, and joint RAN-backhaul intelligence. These areas can be classified under one of two philosophies: upgrading the current backhaul or redesigning key system aspects.

This survey takes a more granular view on one of the areas identified by Jaber – namely, SDN in the mobile backhaul. To our knowledge, such a topic has yet to be reviewed at this level of refinement. As such, the contributions of this paper include presentation and categorization of the latest research in SDN enabled mobile backhauls, leading up to 5G's standardization.

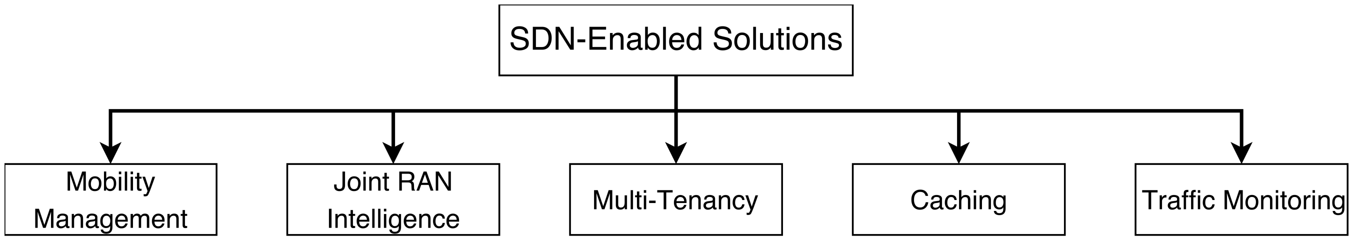

Fig. 1. This Papers's Classification of SDN-Enabled Backhaul Solutions

III. LTE Mobile Networks and the Backhaul

An overview of the LTE network architecture is provided in Figure 2. This discussion is relevant to next generation mobile networks as 3GPP's Release 15 and onwards[1] are actively developed. Key functional blocks as well as the names of the interfaces which interconnect them are illustrated.

The purpose of the mobile backhaul is to aggregate User Equipment (UE) data from the RAN to the core network. Much of the backhaul's current infrastructure is comprised of fibre, copper, microwave, and satellite links [6].

In LTE, UEs connect to what are called eNodeBs and they encapsulate data according to GPRS Tunneling Protocol (GTP) and forward it to the Serving Gateway (SGW). The primary duties of the SGW are to route traffic to its destined tunnel as well as executing handovers between eNodeBs.

GTP tunneling aids in addressing the issue of mobility, which IPv4 does not account for. This way, the UE will be able to communicate with other nodes after changing its link-layer point of attachment, but not its IP. The notion of home and foreign agents are introduced to meet this objective. The importance of tunneling in order to enable mobility with IPv4 is emphasized most recently in RFC 5944[2].

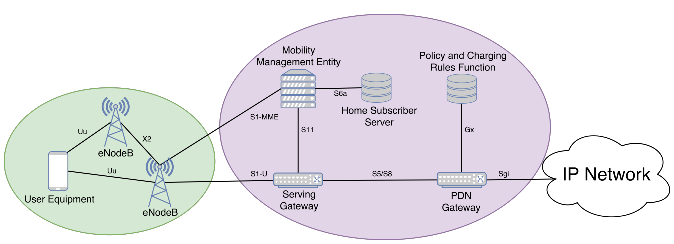

Fig. 2. LTE Network Architecture

Routing between tunnels is subject to rules driven by the Mobility Management Entity (MME), a key control plane element [9]. It takes charge of signaling, authentication, authorization, and management of roaming alongside the Home Subscriber Server (HSS). An HSS is a database for UE details.

Finally, the PDN Gateway (PGW) provides account and addressing services before going out to the Internet. These functions include distribution of IP addresses to UEs, charging, and applying policy and filtering. Policy and QoS details come from the Policy and Charging Rules Function (PCRF).

[1]http://www.3gpp.org/release-15

[2]https://tools.ietf.org/html/rfc5944

IV. Overview of SDN

The core principle of SDN is extracting control logic from forwarding elements and moving it to a central entity – a controller. Such is commonly referred to as decoupling the control and data planes [13]. Ultimately, a single control entity will globalize the network state and simplify network policy management whereby software on the controller programs each forwarding element with flow based rules.

This presents the need for interfacing between forward elements and the control plane as well as from the control plane to network applications. Communication over such interfaces are facilitated by southbound and northbound Application Programming Interfaces (APIs), shown in Figure 3.

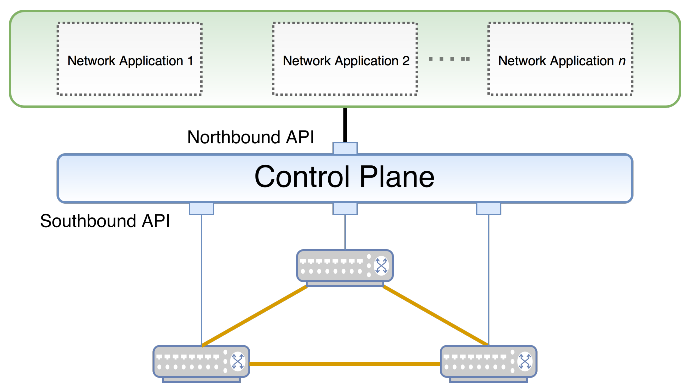

Fig. 3. SDN Decoupling of Control and Data Planes

OpenFlow [16] is a southbound API. It is a protocol which provides the ability of programming flow-tables on different forwarding elements. Rather than including control logic on each element, a single entity can be in charge of programming all of them. This entity is known as a *controller*. McKeown *et al.* have identified a vendor-agnostic set of functions to make this possible. Examples of flow-entries include port forwarding, drop policy, and forwarding to the controller. Such allows for SDN to thrive without vendors having to reveal any proprietary details about their product lines.

As for the northbound interface, Vasconcelos *et al.* [17] note that no clear standard exists. Their high level API attempts to address common deficiencies among existing interfaces such as abstraction capabilities and functionality. Be that as it may, the research community appears to agree that such a design should be RESTful [18]. REST is a design style for networked applications that offers a number of benefits to SDN.

V. SDN Solutions in the Mobile Backhaul

As shown in Figure 1, this survey categorizes SDN enabled solutions in the mobile backhaul accordingly: mobility management, joint RAN intelligence, multi-tenancy, caching, and traffic monitoring. Each of these categories, along with pertinent research, will be introduced in this section:

A. Mobility Management

Handover is a rather expensive process as the MME and SGW require signaling between each other (as well as source and target eNodeBs) and rerouting of a UE's traffic. It will also become more frequent as small cell technologies are integrated into the network from UDNs. This is because each cell will have a smaller serving radius such that mobility over shorter distances will require a handover between cells.

Costa-Requena introduces two different SDN-enabled topologies: controller integration as part of the MME or as part of the S/P-GW to control the transport network [19]. The former would give the controller direct access to mobility events which would amount to more efficient routing paths. The latter would decouple the control and data planes from both the SGW and PGW – hence, a controller is in charge of IP addressing and applying Traffic Flow Templates (TFTs) to flows. The data plane, in this case, would manage GTP during handovers. It is noted that integration with the MME is a more widely implemented approach as it is a less disruptive model.

One such example of MME integration involves retiring GTP to avoid excessive signaling and tunnel reconfiguration latency, as proposed by Wang *et al.* [20]. 802.1ad (Q-in-Q double tagging) VLANs are used for tunneling instead. These VLANs provide the basis for different forwarding rules and QoS. The 802.1ad frame structure is shown in Figure 4:

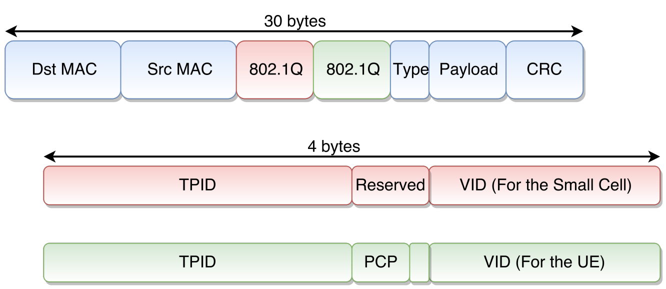

Fig. 4. 802.1ad Frame Structure

Cells, eNodeBs, and the SGW are modeled as OpenFlow enabled switches which are programmed by the controller. As UEs change location, rather than updating the forwarding path on cells and the SGW, the source cell keeps its unique VLAN ID (VID) for that UE. A rule is programmed on to the source cell to take traffic with the original VID and modify it to match the new target cell's VID for that UE. Traffic is then forwarded from the source cell to the target via the X2 interface.

There is a decision threshold for implementing the proposed forwarding chain over the traditional method of updating the forwarding path. The author's results show a clear reduction in signaling with a marginal data delivery delay.

Banik *et al.* [21] also employs 802.1ad in their solution where eNodeBs are clustered into groups, connected by a so-called egress switch with a S-VLAN ID. These switches are networked with, what the authors dub, ingress switches to reach the SGW. The S-VLANs dealt to each egress switch are unique on that egress/ingress switch pair, addressing the issue of VID space and hence scalability of a Q-in-Q scheme.

A Floodlight controller was used in experimentation with hard handovers to show that SDN and Layer 2 routing is a viable and lower cost alternative to GTP in managing mobility.

Rather than 802.1ad, Prados *et al.* [22] have considered an X2-based handover scheme using MPLS. A controller is in charge of installing routes for the backhaul and distributing labels to every edge network element in this scheme. These labels are used as match criteria in the switch flow tables and dictate how traffic is forwarded to UEs. Simulations on a tree topology network with a constant transmission delay yielded a 15.25 ms handover latency from preparation to completion.

The work of Hu *et al.* [23] proposes an algorithm as a module integrated with IEEE 802.21's *de facto* Media Independent Handover Function (MIHF) [24]. It is found by the authors that MIHF cannot easily scale to accommodate the frequency of small cell handovers. The framework is composed of a 2 dimensional decision module and an SDN controlled network.

The *Handover Controller* manages and controls handover and separates initiative and passive handovers as different processes. It oversees two switches and a global database. $Switch_1$ calculates and aggregates network and user metrics to the global database whereas $Switch_2$ selects the best 2 routing paths from a 3 stage pre-selection process. The *Selection Decision Module* implements a 2D cost function to pick one of the two networks passed from $Switch_2$.

This proposed extension has been mathematically proven to cut down on handover times as well as power consumption.

B. Joint RAN Intelligence

Researchers note that the architecture of next generation networks increasingly blur the bounds of the fronthaul and backhaul in order to boost management efficiency. The fronthaul refers to RAN level networks, including BBUs and the Remote Radio Heads (RRHs) which they oversee. This, and the concept of C-RAN, has given rise to the term *crosshaul* – a commmon transport network with legacy support, as explained by Costa-Perez *et al.* [25]. Features offered by NFV and SDN, like decoupling the control and data plane as well as centralized control logic are what fuel this concept.

A high level view of the crosshaul's datapath and key functional blocks can be seen in Figure 5. The unified data plane elements are dubbed Crosshaul Forwarding Elements and Processing Units, or XFEs and XPUs. The former aggregates front and backhaul traffic, whether circuit or packet switched, whereas the latter is in charge of managing virtualized services, processing, and BBUs. A performance evaluation of XFEs has been conducted in [26]. It was found that XPUs must be at most 4 hops away from RRHs to meet processing time requirements outlined for 5G.

The physical layer protocol accommodating front and backhaul traffic is known as the Crosshaul Common Frame (XCF). Adaptation Functions (AFs) are needed to interface between various access technologies that may not be XCF compliant.

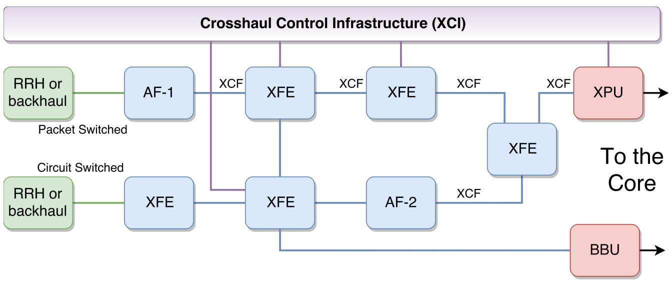

Fig. 5. High level View of the Crosshaul Datapath

The control plane consists of an application layer and, below it, the Crosshaul Control Infrastructure (XCI). This infrastructure combines an NFV orchestrator and virtualization managers with an SDN controller. This design has been considered for the European Telecommunications Standards Institute (ETSI) and OpenDaylight/ONOS compatibility [25].

The XCI is in charge of Management and Network Orchestration (MANO) which provides an abstracted view of network resources and states via the northbound interface in addition to control via the southbound. Through the west and eastbound APIs (as for distributed control planes), the XCI communicates with the 5G core and access MANOs, respectively.

The 5G Public and Private Partnership (5G-PPP[3])'s Crosshaul Project allows for rich services to be provided to its tenants in addition to flexible, software defined, infrastructure. Use cases for the crosshaul are noted as mobile edge computing, media distribution, vehicle mobility, energy efficiency [27], and multi-tenancy [28].

C. Multi-Tenancy

In affiliation with 5G-PPP, the CHARISMA project outlines multi-tenancy via slicing as a prime focus for next generation mobile networks[4]. Network slicing may be used in order to promote multi-tenant systems and reduce CapEx and OpEx [10]. The way slicing accomplishes this is by taking advantage of virtual resources provided by a hypervisor to provision multiple virtual networks over a shared physical backhaul infrastructure [29]. This solution is thereby able to dynamically assign users, or *tenants*, isolated resources to meet their specific needs. This practice maximizes network utilization by leveraging statistical multiplexing gains.

Sherwood *et al.*'s FlowVisor outlines the following fundamental conditions to achieve isolation in slicing [30]:

1) Bandwidth: Regulated on physical links – forwarding elements should enforce the configured rate too.

2) Topology: Slices are to have independent knowledge about the switches and routers over which their network operates; further stressing their isolation.

[3]https://5g-ppp.eu/

[4]http://www.charisma5g.eu/index.php/open-access/

3) Traffic: Traffic belonging to one virtual network must be distinguished from another via some match criteria.

4) Device CPU: Network elemets require CPU slicing in order to dedicate resources to each slice.

5) Forwarding Tables: Must be isolated between slices across network devices. This will allow true independence in the management of QoS in each slice.

Designed for experimentation within CHARISMA, Chartsias *et al.* [31] propose a slice management and orchestration framework and testbed architecture. A virtualized orchestrator deploys network services in this scheme and CHARISMA's own Control, Management, and Orchestration (CMO) platform is used to communicate the desired slicing topology to an OpenDaylight controller. Based on these CMO requests, the controller programs flow tables on a mmWave Point-to-Point switch outfitted by the authors to be OpenFlow enabled.

The controller runs Carrier Ethernet 2.0 as an application which takes care of provisioning transport infrastructure, such as Ethernet Virtual Connections (EVCs). Traffic isolation is achieved through the use of 802.1ad; discrimination is based on each of the two S-VLAN and C-VLAN tags. A slice given to a Virtual Network Operator (VNO) is delegated an EVC with a unique S-VLAN. The customers of that VNO can then be given unique C-VLANs. The experimental validation of this method has been carried out on a 5G testbed.

Martinez *et al.* [32] have proposed a cloud-based SDN/NFV orchestrator which automatically computes, and allocates, resources for virtualized backhauls. These resources can be in the form of virtual SDN controllers or Evolved Packet Core (EPC) elements in the cloud – the authors refer to them as the vSDN and vEPC, respecively. This work expands on a virtualized model of the EPC proposed in [33].

The complete orchestrator architecture consists of various sub modules which oversee the workings of the SDN, cloud, NFV, as well as hypervisor components. In this scheme, an NFV orchestrator interfaces with a cloud based module that instantiates vSDN and vEPC resources. This is done by calling upon lower level sub modules. A cloud based SDN controller, which sets up MPLS tunnels between the RAN and vEPC, is prescribed to each tenant. The vSDN controller shares its network view to the NFV orchestrator. Based on the network performance and usage, the orchestrator may request additional resources from the cloud manager.

Validation of this idea has been practically executed in collaboration with ADVA ONH and the Centre Tecnologic de Telecomunicacions de Catalunya. Virtual Machines (VMs) were used to instantiate the vEPC (in NS-3) and vSDN. Experimental results of this paper boast backhaul tenant setup times of 78 ms and complete VM setup time of 22 seconds.

Li *et al.* [10] have also proposed a multi-tenancy scheme in the realm of 5G crosshaul networks using the XCI for resource virtualization and provider backbone bridge, or 802.1ah, for traffic isolation between tenants. The authors extend the crosshaul architecture with a multi-tenancy application and corresponding API. This application also decides when to (de)allocate network, storage, and compute resources.

D. Caching

Placing high demand content closer to mobile users has also been considered by many groups. Liang *et al.* [34] investigate SDN based optimization techniques in bandwidth provisioning for cache enabled mobile networks under uncertain flow rates. Depending on content popularity, caching can have an extremely positive effect on reducing EPC traffic and latency. Costa-Requena [35] notes that placing caches at the edge wouldn't reach a dense enough user base to exploit content demand patterns. Rather, this can be done at the backhaul.

Defining *user spaces* within OpenFlow switches deployed in the backhaul are the proposed hosts to cache servers in Rodrigues *et al.*'s work [9]. These transparent cache servers can be marketed to content providers (like video streaming) in order to relieve excessive loading on the network – MPEG DASH streaming has been considered. The author's implementation of stateless Deep Packet Inspection (DPI) and GTP/TCP splicing, however, suffered performance degradation since most of the functionality was dependent on the controller.

A cache peering scheme has been realized by Katsaros *et al.* [36] in which tenant VNOs are all able to pull data from a common cache. Caches are Virtualized Network Functions (VNFs) which belong to a micro data center architecture in OpenStack. Rodrigues' previously mentioned network splicing function scheme is used to direct requests to the virtual caches. SDN is used to dynamically set up a route between UEs and the caches when a cache hit is deemed likely.

Rather than a common cache, Li *et al.* [37] have investigated cooperative caches. In this scheme, local caches are maintained at the edge network and in case of a miss, off-site locations are queried through the backhaul. This is done by a crosshaul load balancing framework with SDN roots.

Local cache hits are the first priority. If the local cache turns up a miss, content and connection tables are maintained by the controller which coordinate the off-site caches available to the UE. The connection table represents a connected graph of base stations with caches and X2 links between them. The content table is a list of cached objects for all base-stations. A link availability table is also kept to check if a cache is available to a particular UE.

The last resort is going through the Internet for the desired content. Load balancing is in place in the event of multiple off-site cache hits – the more economical option is chosen. Given the network architecture, and predefined parameters, the authors formalize their objective and derive an optimization problem which is tackled by the proposed algorithm. The authors found that joint load balancing reduces load by up to 12% as compared to only backhaul load balancing.

E. Traffic Monitoring

Legacy monitoring systems are of high complexity, generally uncoordinated, and vendor specific, coming with many challenges in large scale implementation. As an increasing portion of the mobile architecture becomes virtualized, it is apparent that these monitoring systems are not optimized to take full advantage of such an environment. With end-to-end visibility, provided by SDN, monitoring systems can become greatly simplified and more effective. This is Liyange *et al.*'s [38] vision with Software Defined Monitoring (SDM).

This solution consists of an SDM controller (running on Floodlight) which extends upon standard controllers for better resolution on a per packet basis. This is done with packet sampling. A control interface extension of OpenFlow is implemented for routing and delivering messages to monitoring probes. Monitoring probes collect information about the network and come in two flavors – passive or active probes. Active probes can modify traffic. A probe manager determines where, either physically or virtually, a probe should be located. The probe information is aggregated to the network management module which provides a holistic view of the network's performance, security, and behavior – this is packaged into a User Interface (UI) called the network monitoring dashboard.

Experimentation was carried out in MiniNet with OpenSwitch. The authors have considered isolating a security threat from propagating through the network through their SDM framework. Preset rules are defined for attack traffic and a course of mitigation is chosen. After quarantining the network, the controller allows affected devices reconnect.

On their testbed, it took on average 18.5 seconds between 10 trials to identify the threat and update switch flow tables to drop the target traffic. The authors note being able to design general purpose applications for any network topology, placement of the controller, and translating traditional methods to an SDN environment as key challenges for SDM.

VI. Conclusions

In this paper, we have investigated the emerging paradigm of SDN in relation to the needs of next generation mobile networks. Clear challenges are associated with their ambitious requirements on data and latency, which gives way for a number of proposed solutions. While no single technology will be able to address the entirety of these challenges, it is apparent that SDN is capable of playing a leading role in this effort. It is widely acknowledged that decoupling the control and data planes can reduce management complexity (as well as CapEx and OpEx) and provide greener network operation.

One such challenge is designing a backhaul architecture that will be able to keep up with the massive volume of data coming from small cell based UDNs. This is the principle subject matter of this paper. Of the surveyed literature, five areas where SDN can significantly benefit mobile backhauls have been discussed – mobility management, joint RAN intelligence, multi-tenancy, caching, and traffic monitoring.

Researchers have investigated alternatives to GTP as well as the concept of merging the fronthaul/backhaul transport network into a single crosshaul. Such a crosshaul has shown positive implications for other SDN enabled technologies such as caching and multi-tenancy which lighten the burden of the backhaul. End to end network visibility also makes traffic monitoring based QoS a reality. Each of these categories have shown varying range of progress and surely deserve consideration in the next phase of mobile network evolution.

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