dLTE: Building a more WiFi-like Cellular Network

(Instead of the Other Way Around)

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ABSTRACT

The radio interfaces and network architectures of WiFi and cellular systems are converging along many dimensions. While both systems are largely adopting the centralized architecture of traditional cellular deployments, this design comes with fundamental disadvantages that limit how these networks grow and develop. As a response, we present Distributed LTE (dLTE), an architecture offering the high radio performance of licensed and coordinated waveforms as well as the openness to organic expansion and growth of traditional WiFi. We challenge the assumption that good performance requires a centralized packet processing core, and propose hybrid approaches to coordination that prioritize system openness. We argue that dLTE is a particularly good fit for rural areas, where the LTE waveform is more appropriate than WiFi, yet it is uneconomical for centralized providers to deploy traditional cellular systems.

1 INTRODUCTION

Consumer wireless technologies have seen exponential adoption and network growth over the last twenty years. Ubiquitous wideband wireless data connectivity is now the standard in urban and peri-urban areas around the world. Two independently and simultaneously evolving technology stacks have been responsible for this communication revolution: cellular data networking (beginning with 2G GSM-GPRS and presently focused on 4G LTE) and the IEEE 802.11 family of standards, commonly known as WiFi.

At their inception, these two standards occupied two distinct points of the overall design space, with different stakeholders and use cases. WiFi enabled non-expert users to deploy wireless local area networks in their homes and offices, used the interference-prone 2.4GHz and 5GHz ISM bands to support unlicensed operation, and employed a distributed MAC protocol to remove the need for central coordination [50]. WiFi extended existing IP networks, and in most deployments acted as a gateway to services hosted on the public Internet.

On the other hand, cellular networks were designed as high performance wide area extensions to existing telecom networks. From their wireline ancestors, cellular networks needed network primitives for user billing, tracking, regional mobility, call circuit allocation, and phone system interconnect [40]. Furthermore, telcos are legally obligated to provide regulated levels of quality and availability, motivating designs based on licensed spectrum with scheduling and quality-of-service (QoS) guarantees. Extensions to the network were planned and controlled by experts to manage interference and resource provisioning between radios. To achieve this level of control, cellular networks relied on a set of specialized network functions kept in a centralized location under the operator's control, known generally as the cellular core network and specifically in LTE as the Evolved Packet Core (EPC).

As they have evolved, cellular and WiFi have sensibly borrowed ideas from each other, resulting in systems that share characteristics in the physical layer, MAC, and, more recently, overall network architecture. WiFi has adopted cellular's transmit power control [50], inter-access point (AP) mobility [18], central authentication [17], and high scalability through scheduling and load-balancing optimizations [14]. Conversely, cellular networks have adopted WiFi's packet switched IP substrate [20], OFDM modulation [36], and support for unlicensed spectrum [49]. Most notably, new breeds of centralized WiFi networks actually use cellular EPCs for authentication and traffic management, enabling users to seamlessly move between WiFi and cellular [11]. Upcoming capabilities based on the Citizen's Broadband Radio Service (CBRS) in the US will allow neutral hosts, like concert venues or businesses, to extend centrally managed LTE service from incumbent cellular operators into private indoor environments traditionally served by WiFi [26].

The advantages of centralization (scale, easy operation, and better performance, among others) are hard to argue with. However, centralized architectures are not appropriate in *all* scenarios, and a lack of open options could lead to negative long term effects on the health of the access ecosystem [47]. A common and obvious response to centralization is to use and promote existing decentralized technologies based on WiFi. However, the LTE waveform offers advantages over

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	Open Core	Closed Core
Unlicensed Radio	Legacy WiFi WiFi Mesh	Enterprise WiFi Private LTE
Licensed Radio	**dLTE**	Telecom LTE 5G Cellular

Table 1: A division of the wireless design space, highlighting the unexplored quadrant addressed by dLTE.

WiFi in many cases, and we believe that it is possible to drive decentralization *in the other direction*, building an open and peer-to-peer version of LTE that maintains its advantages over WiFi. To this point, we introduce Distributed LTE (dLTE), an LTE architecture that uses a global registry for peer discovery, but defers responsibility for interference coordination, mobility management, and packet processing to individual APs over a standardized, self-organizing network protocol.

The dLTE registry is open, taking its design from federated peering in the core Internet. New APs are free to join at any time, and coordinate with existing nodes to better utilize the radio resources in each local collision domain. This approach is philosophically similar to the openness of legacy WiFi, but with the efficiency and range advantages of a coordinated access network using licensed spectrum.

Throughout this paper, we assume that the reader has working knowledge of legacy WiFi systems, and provide background on cellular network core architectures in Section 2.1.

2 CENTRALIZED NETWORK CONVERGENCE

2.1 The Cellular Core Network

Cellular networks have been shaped by different constraints than IP networks, which provide best-effort connectivity and operate as black boxes to simplify their architecture [31]. Due to the functional requirements described in the previous section, cellular networks maintain flow state in the network to provide end-to-end guarantees and allow for rapid mobility between cells. All packets are tunneled to the cellular core (EPC), and can be monitored and inspected before forwarding [40].

Unlike the Internet, cell networks are closed to organic expansion. New LTE access points cannot be added at users' will; only clients to existing APs are universally accepted. This architecture gives the operator unilateral say on what APs extend the network's reach. Some carriers offer femtocells for customer deployment to attach to their EPCs through the customer's own Internet connection, but users of this hardware still pay the carrier for this privilege, even though they bear all costs for backhaul, power, maintenance, and the equipment itself [1, 13]. Non-extensibility is reinforced through architectural decisions made in cellular networks as well: reliance on symmetric key authentication drives a need to securely store secret keys and connection metadata, and protocol level assumptions that there will always be a small number of addressable cores cement the positions of regional scale telecoms.

Ironically, new EPC implementations are being built on all-IP substrates [22], and designs based on software defined networking and network function virtualization are being explored to allow for better scalability and fault tolerance while still meeting QoS guarantees [2, 39]. In these cases, even though the lowest layers of an EPC may run on IP and ethernet, the user's traffic is still centrally tunneled, managed, and tracked through the EPC before reaching the public Internet in a way that is counter to traditional IP forwarding.

2.2 The Closed Core Model in WiFi

Industry seems to be converging on the closed core as the de-facto means to organize and coordinate multiple access points, across both LTE and WiFi-based access technologies [21, 34, 43, 44, 46]. High performance networks requiring mobility and central authentication are more straightforward to implement with one central core, and the 3GPP cellular standards offer a well defined core interface for commercial implementations. Like cellular networks, enterprise WiFi networks with many overlapping access points and large numbers of concurrent users benefit from spectral coordination and out of band mobility management [34]. Telecommunications companies also benefit from WiFi attached to the EPC: WiFi access points can absorb low mobility and non-emergency traffic to free up precious licensed spectrum while still allowing the telco complete control over the customer [21, 43].

WiFi architectures with closed cores have appeared across a range of settings from university campuses and stadiums to offices and homes [5, 6, 10, 46]. Despite these trends, WiFi can still be used in a decentralized fashion to create simple local Internet access networks as needed. Unlike telephony networks, WiFi networks don't need to support emergency services, don't strictly require L2 security, don't need to support rapid mobility, and don't need to centrally bill users. Without these constraints, we argue that a closed core architecture may be unnecessary even for LTE access networks.

3 WHY DISTRIBUTED LTE

If cellular architectures are harming access technology, why not just advocate for WiFi? We see two reasons: first, most people already get their access through cell networks, where a central EPC is a chokepoint to the Internet. Second, LTE is uniquely suited to solving the problem of universal Internet access.

3.1 Democratizing Cellular

The centralized control of cellular networks contrasts with the Internet, which is fundamentally a series of organizations ("autonomous systems") connected over the peer to peer Border Gateway Protocol [48]. While consolidation exists in both Internet and telecom industries, the open nature of the Internet still allows hundreds of small service providers to operate and interconnect with their own infrastructure [8], whereas there exist only a handful of mobile operators with their own networks in the United States. In this context, empowering individuals and communities to deploy efficient mobile networks provides an important means to resist the consolidation of telecommunications to a few large players that was the Bell system [47].

Decentralization has also been viewed as a way to create more robust, private, and dynamic systems that can operate cheaply through cost sharing and collaboration [33]. We believe that an open LTE access network could bring broadband connectivity to places where it is currently uneconomical by lowering financial barriers to deployment and empowering locals to address their own connectivity needs. Particularly in remote areas, robust connectivity can enable new approaches to conservation, agriculture, and land management.

3.2 Wide Area Coverage

Decentralized architectures are well suited to providing rural access as they allow for a heterogeneous set of actors to collaborate and share resources; this is one reason why so many rural access initiatives use WiFi. We propose that LTE is *better* suited to wide-area rural coverage, due to its spectrum band usage and waveform, and therefore a distributed and open form of LTE could be a key convergence of technologies and architectures towards universal Internet access.

Spectrum Bands: WiFi largely operates on two ISM bands: 2.4Ghz and 5Ghz. They were selected for 1) having poor propagation to limit interference between networks, and 2) being unlicensed and available for new uses. While this is critical for urban areas, where spectrum is highly occupied, most spectrum in rural areas lacking network coverage is, by definition, available. Researchers previously proposed refarming this for GSM [23]. Unlike WiFi, LTE supports over forty different bands encompassing both licensed and unlicensed frequencies. LTE basestations and clients are commonly available at reasonable prices in bands with better propagation and higher allowed power than the ISM bands, such as bands 5 (850MHz), 30 (800MHz TV White Space), or even 31 (450MHz). Rural access networks using the LTE air interface can take advantage of the cellular ecosystem's economies of scale. The range of options allows selecting the right frequency for rural access without being confined to the limits of the ISM bands or needing expensive custom hardware.

LTE Waveform: LTE outperforms WiFi over the more tenuous links common in rugged areas. It is explicitly asymmetric, optimizing for an advantaged basestation and a low-power handset. LTE's SC-FDMA uplink modulation allows higher power transmission and greater range from mobile devices, and hybrid ARQ increases throughput under weak signal conditions. LTE's scheduler also handles longer links by explicitly compensating for propagation delay. These characteristics map well to rural deployments, where a single basestation can be deployed on existing structures with reliable power (like barns or grain silos) to cover a large area with a single point of maintenance. Technologies designed for local area networks in urban areas have insufficient range for rural areas; "wide area" technologies operate at scales more appropriate to farms, ranches, and fields.

4 DLTE ARCHITECTURE

As a response to the trend towards closed-core network architectures, and from a desire for a better wide-area access solution, we propose an architecture for high performance, yet open and distributed, fronthaul with LTE. Our proposed system, dLTE, is a federated network of individual LTE access points. Like legacy WiFi networks, each dLTE access point functions as a complete standalone network, with no shared EPC. Yet unlike legacy WiFi networks, dLTE allows access point owners to peer with neighboring access points to collaboratively improve performance and handle mobility and leverages the LTE waveform to provide wide area coverage in the last-mile. dLTE makes three changes to enable this decentralized operation:

(1) Moving all required EPC functions into a "local core" stub at each AP
(2) Recommitting LTE to the end to end model to allow flexibility and performance without centralization
(3) Embracing low overhead licensing schemes with federated decision making to enable scalable, yet open, coordination of radio resources.

4.1 Local Cores

To maintain compatibility between the dLTE access point and standard clients, we deploy an EPC stub at each AP, virtualizing the required EPC components (S-GW, P-GW, MME, and HSS) in software on a local processor. While the AP must perform all functions the client expects from a standard EPC, in the dLTE architecture we minimize complexity by paring its functions down to only those directly required by the client. The stub performs mutual authentication with the client and sets up the expected control plane and data plane tunnels through the LTE radio basestation (eNodeB), but does not manage mobility, perform networking between physically discrete EPC components, or handle user billing. Just like WiFi, access point owners maintain routing control since dLTE terminates all LTE tunnels at the AP and outputs the client's *unencapsulated* IP traffic. The amount of processing required by a stub core is minimal, and its deployment requirements are trivial compared to the radio itself. Furthermore, each stub can be independent of others, so the one stub per site model naturally scales as the total number of APs increases.

4.2 Reliance on End to End Services Over IP

dLTE access points remain simple because they provide clients with nothing more than a public Internet connection. Just like a WiFi hotspot, dLTE relies exclusively on third-party "over the top" (OTT) services to provide higher-level user capabilities (such as security, authentication, and mobility), and explicitly does not provide interconnect with the Publicly Switched Telephone Network.

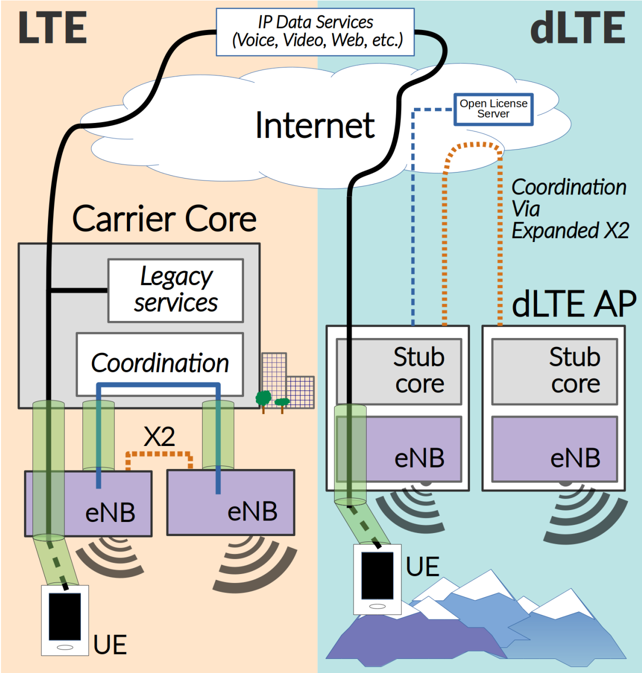

Figure 1: Comparing LTE with dLTE. Both support spectrum coordination to avoid interference. dLTE provides direct access to the Internet from the AP, versus LTE where all traffic tunnels through the EPC. dLTE coordinates directly with peer APs via the Internet, while LTE coordination is mediated by the carrier EPC.

By explicitly not providing these traditional telecom services, dLTE encourages a service ecosystem tailored to individual needs that can evolve over time without changes to the underlying access network. By exposing all services through the multiplexer of the Internet, users can opt into the services that they want and the barriers to entry for new offerings are greatly diminished.

Security and Authentication: While LTE builds strong mutual authentication of the client and network directly into the protocol, we can intentionally undermine it to enable dLTE. LTE's authentication relies on symmetric key encryption at the link layer, so users can simply pre-publish their keys to allow any associated dLTE AP to authenticate with them. The GSMA recently finalized specifications for remotely provisionable "e-SIMs," which allow for holding multiple identities on different networks simultaneously, and make it easier to generate and deploy new identities to clients [4]. With such flexible systems, end users could simultaneously maintain an open dLTE SIM alongside other secured SIMs for different networks.

Just like the Internet, dLTE does not require or enforce L2 security or network authentication, though this does not preclude individual APs from using link-layer encryption. This opens clients to link layer eavesdropping– the open nature of the system makes it easy to "honeypot" targets of interest, as is the case in public "Free WiFi" access points today. Just like in these WiFi systems, applications requiring security must rely on end to end transport layer security or use a tunnel/VPN; no trust is placed in the AP substrate.

For authentication, dLTE relies on end to end notions of identity, completely removing identity from the LTE access layer (through the previously mentioned key publication) to facilitate internetwork mobility. However, other OTT identity systems (e.g. social networks and email providers) have already achieved widespread adoption, for better or worse. At the same time, web identity standards are rapidly evolving, with open standards like OAuth, U2F, and FIDO2 allowing users to establish identities with strong security between a wide variety of devices and services [7, 30].

Service Mobility: dLTE does not support IP address mobility, leaving service continuity to endpoint transport and application layers. In centralized LTE, the EPC's mobility management entity (MME) updates tunnels for each client as it moves across eNodeBs, carefully attempting to mask its mobility. Conversely, in dLTE, clients are quickly assigned a new publicly routable IP address as they change APs; this allows the routing plane to remain static. While network mobility is known to be challenging, current-generation transport protocols make this approach more feasible than it was in the past, incorporating zero RTT secure flow resumption, forward error correction to mask discontinuity, non head of line blocking, and multiple IP address support for client managed handoff [29, 41]. Handling mobility at the endpoints obviates the need for in-network mobility management, decreases buffer bloat, and gives the client more information to compensate in an application appropriate way. Most importantly, we note that applications are *already* incorporating these protocols to improve general performance and allow endpoint mobility across WiFi and LTE [29].

Clients moving at high speed through dense AP distributions place tight performance constraints on handover between APs. dLTE's IP address instability and use of the Internet for inter-AP coordination may break down under such scenarios, particularly as the client's time on a single AP approaches the same order of magnitude as a round trip to an in use OTT service. This could be largely mitigated by moving OTT services closer to the network edge, or by building a hybrid system with a small number of geographically co-located eNodeBs assigned to each dLTE core.

4.3 Spectrum

All radio networks must gain access to open spectrum for transmission. Traditional telecoms use centralized coordination, which offers efficiency advantages, but comes at the cost of openness. dLTE proposes a novel division of responsibilities for spectrum management, using a lightweight open public license database for peer discovery, and peer-to-peer organization for decentralized coordination.

Licensing and Discovery: Spectrum access through licensing alleviates scaling bottlenecks faced by unlicensed systems: a license database ensures that all transmitters in the band are known, thereby mitigating the hidden terminal problem. Furthermore, it permits operation in a wider variety of bands, some with better propagation characteristics for specific use-cases. Licenses also provide recourse for operators to resolve issues via such traditional means as face to face discussion or email. While licenses have traditionally been inflexible, expensive, and time consuming to acquire, new paradigms in licensing are making licensing more practical. In the United States, the Citizen's Broadband Radio Service (CBRS) will use automated Spectrum Access Systems, contracted by the FCC and reachable via API, to dole out geolocated licenses to midband (3.5GHz) spectrum based on local demand [38].

While CBRS is a centralized service limited to the United States, it is an example of an *open* service, governed as a public resource and open to any user who conforms to the protocol. Different registry designs are also possible, such as a federated system similar to the DNS. Systems have also been proposed using public blockchains to remove all centralization from the licensing process [27]. The dLTE architecture does not require a particular license paradigm, as long as the registry is open and accurately reports which access points operate in each region.

Out-of-Band Coordination: With a structured list of access points in the same RF contention domain available from the licensing registry, it becomes feasible to manage RF utilization directly peer-to-peer. dLTE access points establish connections with their neighboring APs via a standardized protocol over the Internet backhaul. AP owners can elect to either run their access points in a default fair sharing mode, or fuse resources with their neighbors in a cooperative mode. Aside from selecting the mode, all optimization and day to day management is automated. If fair sharing, the APs programatically coordinate the bare minimum of fair time-frequency sharing of the underlying RF resource between the APs, more efficiently achieving an equilibrium with similar fairness characteristics to what WiFi achieves today. In cooperative mode, the APs programatically optimize for maximum joint RF performance, *taking advantage of the resources of both access points*. Cooperation allows for client handoff across the APs, QoS aware joint flow scheduling between APs, and the assignment of the best AP to serve each client device. These improvements are impossible to achieve under legacy WiFi's independent AP model.

The LTE specification already defines the X2-AP interface for LTE eNodeBs to share handover and spectrum coordination information in a peer to peer manner [19], and much research and development has been dedicated to self organizing network optimization approaches [24, 32]. We do not attempt to make a contribution to the theory of self organizing networks in LTE, but rather seek to provide an operational model to apply it across administrative domains.

dLTE APs will run a version of X2 extended with information about the dLTE operating mode and dLTE peer status. The X2 interface is relatively low bandwidth, but when backhaul constrained the level of coordination can be minimized [28]. The protocol will need to be standardized across APs, and compatibility can be enforced through the licensing process. By giving AP operators the agency to independently opt into cooperative operation with their peers, the network is open to organic decentralized expansion while achieving the benefits of tight RF coordination.

Figure 2: dLTE prototype components: A mini-computer, commercial eNodeB, and off-the-shelf handset

4.4 Tradeoffs

dLTE sacrifices the mobility management, L2 security, and integrated services of LTE. By putting basestations in the hands of users, it also forgoes the professional management, monitoring, and network planning provided by a traditional telecom. These are important features in an urban setting with tight spectrum, dense AP and user distributions, and rapid mobility via car and train. dLTE is less appropriate in these environments, but also less important. In dense areas the centralized model works well, and demand is high enough to ensure robust market competition among providers. In rural and underserved areas, however, we believe that dLTE's downsides are outweighed by the openness, flexibility, and individual empowerment of a WiFi-like architecture.

5 ONGOING IMPLEMENTATION

Our research group is currently working towards real-world deployments of dLTE. We have deployed a standalone network in partnership with a rural school in Papua, Indonesia. The network is data only, with voice and messaging provided via OTT services (e.g. WhatsApp). Initial reactions have been positive, and users seem satisfied with the performance and limitations of having only a data connection. The network operates under a permissive secondary use non-compete license, using unoccupied UHF spectrum in LTE band 5 (850 MHz) to provide broad coverage. One site covers the entire town, and is deployed on the gym where power and backhaul were available. The deployment cost less than $8000 in materials, including two commercial eNodeBs (for two sectors), two 15dBi antennas, an off the shelf computer for the EPC, and cabling. All EPC software is free and open source [35, 45].

We are in the process of deploying a second site to test the impact of dLTE's mobility approach on real-world usability.

6 RELATED WORK

WiFi Mesh Networks: The network of cooperative dLTE APs we propose is similar in spirit to a WiFi mesh network. However, LTE has protocol-level features missing from WiFi that make cooperative spectral optimization and resource allocation more efficient, all without client device modification. For example, state-of-the-art WiFi mesh networks can cooperatively and heuristically assign channels to client devices to minimize AP interference [42] and even perform seamless handover via packet duplication at neighboring access points [12]. In contrast, LTE has built-in coordinated channel assignment, scheduling, and supports efficient client handover that does not require any packet duplication. APs do not have to do additional work to hide the handover or let clients keep their IP addresses, allowing fast re-authentication technologies to handle the address change.

Private LTE: Private LTE, or LTE network-in-the-box solutions, are currently being touted by telecom service providers as a new option for high-performance enterprise applications such as mining sites or factories [15]. These networks may use licensed assisted access with a telco partner or MulteFire, an LTE specification developed for the 5 GHz unlicensed frequency band that coexists with WiFi [3]. Private LTE is essentially small-scale traditional LTE, with a central EPC running on premises or remotely in the cloud. Any additional APs must attach through this EPC: a marketed advantage of private LTE is the added security of restricting communications via the managed core [9]. In contrast, our architecture addresses a different use case, creating an "open core" where individual dLTE APs can join the registry and peer with nearby APs on a case by case basis. dLTE forgoes the security advantages of private LTE's single core in exchange for the possibility of organic growth and inter-organization coordination.

Distributed LTE architectures: Researchers have also explored other mechanisms for building a distributed LTE network. Qazi et al., for instance, redesigned the core network to scale laterally on standard commodity datacenter hardware [39]. This solution, however, remains centralized in a datacenter core network and does not address how new endpoints can be added organically to the network edge.

Most aligned to our work is Jover et al.'s distributed HSS [25], which uses a blockchain primitive to implement a fully distributed authentication server for LTE. Their approach requires a new asymmetric-key based procedure for authenticating user devices, and unlike dLTE, cannot interoperate with current cellular infrastructure. Jover et al. also do not address spectrum, focusing only on authentication. dLTE builds from the same ethos, but proposes an architecture that is both backwards compatible with existing infrastructure and allows dynamically coordinating scarce spectrum.

Distributed Spectrum Coordination systems: Spectrum coordination can be centralized or decentralized. Cognitive radio, the distributed sensing of available spectrum, is seen as the alternative to centralized databases [16]. Notably, TV White Space spectrum databases allocate spectrum inside of the recently relicensed TV bands. Both Google and Microsoft operate large, centralized, cloud databases for spectrum management. Our system builds from these approaches, using an open database, centralized [38] or decentralized [27], to aid peer discovery for explicit out of band coordination.

7 FUTURE WORK

We are excited to continue exploring the design of systems inspired by dLTE. One area is investigating how tools can support users in making provisioning decisions beneficial to the health of the entire ecosystem. We are interested in how both human-in-the-loop and automated systems can help avoid the degradation of WiFi typical in chaotic deployments, and the practical concerns of deploying and maintaining collaborative systems with real world users.

The forthcoming 5G-New Radio cellular waveform offers more improvements for area connectivity, with support for new bands, three dimensional beamforming, massive MIMO antenna arrays, and new primitives for authentication [37]. Incorporating 5G technology into the dLTE framework would further improve the capabilities of the dLTE system.

We are also interested in additions to the system specifically targeting Internet access for rural remote and low-resource regions where backhaul links are heavily constrained. We are planning to explore multi-hop approaches to sharing and aggregating bandwidth between neighboring LTE APs. Such networks could provide redundancy for users in emergencies when the backhaul link goes down, and bring LTE's scheduling primitives and beamforming to bear on mesh designs.

8 CONCLUSION

We argue that the current proliferation of closed core network architectures in wireless systems is by convenience, not necessity, and that there is no fundamental reason that coordinating the RF access network requires a closed core network. The proliferation of designs closed to organic expansion could have a limiting effect on the future ecosystems of wireless devices, and we as networking researchers should ensure that such a future is an active choice by the community, rather than simple acquiescence to persistent commercial pressure.

As an alternative to growing centralization, we presented the dLTE architecture, built from high performance LTE primitives but inspired by the openness and simplicity of legacy WiFi. We believe that giving local access point operators the tools and agency to coordinate their systems with their neighbors, in a protocol mediated way, allows for the sustainable organic growth witnessed in the Internet itself.

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