Bridging the ICN Deployment Gap with IPoC: An IP-over-ICN protocol for 5G Networks

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ABSTRACT

Information-centric networking (ICN) is a new networking model that addresses content directly rather than addressing end-hosts. An ICN-based networking layer aligns better with application needs; it provides content-centric security, caching, and intelligent packet forwarding making it useful to both users and service providers alike in terms of efficiency, security, and mobility. ICN has recently received considerable attention; researchers have explored its benefits for diverse use cases such as large-data applications, building automation systems, vehicular networks, and IoT applications. While ICN provides significant benefits to all these application areas, one significant challenge that remains to be addressed is real-world deployment. An ICN-only network will require all IP applications to be rewritten to use ICN natively, a tall order in a world with millions of applications connected to the Internet. Though this problem affects all IP applications, we use mobile applications as the driving example for this work. An ICN based network can benefit smartphone users with higher throughput and lower service interruptions and at the same time, allow mobile service providers to utilize their network better and reduce protocol complexity.

In this paper, we propose IPoC, a general purpose tunneling protocol that enables all IP applications to utilize ICN networks. We implement the IPoC protocol using Named Data Networking (NDN) semantics and using mobile communication as the driving example, compare our protocol performance with native IP. We show that the protocol overhead and performance degradation of IPoC is minimal which makes it suitable for immediate deployment. In return, we show how NDN and IPoC can bring ICN benefits to 5G mobile networks by simplifying the mobility plane, introducing intelligent functionality, and reducing network complexity.

CCS CONCEPTS

• **Networks** → **Network protocol design**; **Network simulations**; **Network performance evaluation**; **Mobile networks**; **Public Internet**; **Network experimentation**; **Wide area networks**; **Network mobility**; **Naming and addressing**;

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NEAT'18, August 20, 2018, Budapest, Hungary

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ACM ISBN 978-1-4503-5907-8/18/08...\$15.00

<https://doi.org/10.1145/3229574.3229575>

KEYWORDS

Information Centric Networking, Named Data Networking, IP over ICN tunneling protocol, ICN deployment, 5G mobility plane, Mobile Handover, ICN for 5G networks, Dual Connectivity

ACM Reference Format:

Susmit Shannigrahi*, Chengyu Fan*, and Greg White. 2018. Bridging the ICN Deployment Gap with IPoC: An IP-over-ICN protocol for 5G Networks. In *NEAT'18: ACM SIGCOMM 2018 Workshop on Networking for Emerging Applications and Technologies*, August 20, 2018, Budapest, Hungary. ACM, New York, NY, USA, 7 pages. <https://doi.org/10.1145/3229574.3229575>

1 INTRODUCTION

Information-Centric Networking (ICN) provides key benefits such as stateful forwarding, in-network caches, user mobility, and others, that make it attractive as the future Internet architecture. Researchers have demonstrated ICN's benefits for diverse applications such as large data applications [14] [23] [5] [20] [21], building automation [19], vehicular networks [6] [7], and IoT [2] [4]. Furthermore, ICN can support features that are complex to implement with IP's end-to-end semantics. An example better illustrates this; currently, the handover of a mobile device to a new base station requires complex protocols involving packet queuing, end-to-end path setup, and transitioning existing packet flows to the new path. On the contrary, an ICN based handover can simply start forwarding packets on the new link, thereby eliminating much of the delay and complexity associated with the current IP based protocols.

Despite the advantages, application compatibility remains a significant hurdle that stands in the way of deploying ICN-only networks since existing IP applications are constrained to use only IP networks. While we could address this obstacle by requiring that all IP applications be rewritten to use ICN natively, it is a tall order in a world with millions of connected applications.

In this work, we describe IPoC, a general purpose IP over ICN tunneling protocol. IPoC is transparent to the IP applications on either end; applications remain unchanged until they are ready to run directly on an ICN network. While IPoC can be implemented using either the NDN protocol or the CCN protocol, we use NDN primitives for our prototype implementation. Our protocol is also generic compared to the previous works on ICN tunneling [17] [24] [12] and works for any IP based communication. In this work, we envision IPoC as a user-plane tunneling protocol for the 5G Core network (5GC) that replaces the GPRS Tunneling Protocol (GTP) currently used in the LTE Evolved Packet Core (LTE-EPC).

This paper has two distinct sections. The first part discusses the IPoC protocol details and the second part illustrates its potential usage in the 5GC. We compare IPoC's performance with GTP and show that IPoC/NDN is capable of similar network performance to GTP. We also demonstrate that by leveraging the elegant, built-in

Figure 1: IP packet paths in IPoC.

support for mobility provided by NDN, IPoC/NDN can substantially lower protocol complexity in 5G mobile networks and support features such as dual-link utilization [26] and intelligent handover that are currently difficult to implement in LTE-EPC.

2 RELATED WORK

Several previous works have investigated techniques that can act as a bridge between IP and ICN networks. Trossen et al. [24] proposed an architecture that enables IP applications to communicate with an ICN network core using a Network Attachment Point (NAP) that interprets each IP based protocol. Similarly, Refaei et al. [17] proposed a general purpose, extensible IP-to-NDN gateway that translates between NDN and IP packets based on pre-defined rules. Interpreting every IP-based protocol is likely to be cumbersome due to a large number of protocols in existence; further, it is unclear how these protocols would handle TLS connections which are becoming increasingly commonplace. On the contrary, IPoC simply transports IP packets across an ICN network, without the need for interrupting end-to-end communication between the endpoint applications.

Moiseenko et al. proposed TCP/ICN [12], a protocol for carrying TCP traffic over NDN. However, this protocol works only with TCP based applications, designed around the current TCP state machine, and is hard to modify to support other IP based protocols such as UDP, QUIC, LEDBAT, and others. In contrast, our protocol is generic and can carry any IP traffic without protocol specific modifications.

Wu et al. investigated the issues for incrementally deploying NDN in LANs [28] using dual-stack switches that support both NDN and IP protocols. While the dual-stack devices help with NDN deployment, they do not provide enhanced network support for existing applications. On the contrary, our approach can potentially simplify existing protocols and improve application performance.

3 THE IPOC PROTOCOL

In this section, we discuss the essential constructs of the IPoC protocol. Fig. 1 outlines the protocol and shows the two primary entities that our protocol defines: the IPoC Client and the IPoC Gateway. A network may have many Clients and several Gateways. Though our protocol is generic, we use LTE-EPC as our driving example to explain the protocol details.

The IPoC Client exists on a User Equipment (UE) such as a smartphone and acts as a tunnel endpoint, much in the same way a VPN application does. All IP traffic generated on the UE are forwarded via the local IPoC Client, which encapsulates them in NDN Interest messages and sends them into the NDN network. Intermediate routers speak NDN, forwarding Interests towards the IPoC Gateway.

The IPoC Gateway exists at a boundary between the NDN-only mobile network and the IP network and advertises to the IP network that it provides reachability to one or more IP prefixes. The IPoC Gateway also acts as a tunnel endpoint. It receives Interest messages, unpacks the IP packets, and forwards them into the attached IP network. It also encapsulates the return IP traffic into NDN Data packets and forwards them towards the Client which then unpacks and forwards the IP packets to IP applications.

Figure 2: Evaluation topology.

IPoC uses both Interests and Data packets as vehicles for carrying IP packets. While arguments exist both for and against using Interests packets for carrying data [10], we do not try to answer this architectural question in this work but focus on providing a way for NDN deployment. Besides, several NDN applications (e.g., building automation, secure sensing) already use Interest packets for carrying data, either in a payload or as a name component. In this work, we have used Interest payloads for carrying data since appending the payload to the name increases PIT memory usage.

3.1 IPoC Naming Conventions

Like any NDN based protocol, the primary construct of IPoC is the Interest and Data names. In our implementation, we use hierarchical names between the Client and the Gateway. These names use the following naming convention:

/IPoC/<hex_ipaddr>/<b64_seq>

The components of the name are as follows:

- **IPoC** - The reserved name prefix used in all IPoC messages.
- **hex_ipaddr** - For IPv4 addresses, this field comprises four separate name segments, each representing a single octet of an IPv4 address encoded as a hexadecimal string. For example, an Interest from a Client with the IPv4 address 11.0.0.12 would use "0b/00/00/0c" for this name component. Note that Fig. 1 uses decimal octets for clarity.

Figure 3: IPoC performance evaluation for single file transfer.

- **b64_seq** - This is a base64-encoded value representing an Upstream Sequence Number.

If the mobile operators need to support private IP blocks [8] within their networks, we can simply extend our naming convention to include a more specific prefix, such as `/IPoC/<zone_id>/<private_ip>`, as part of the client initialization process. This simple modification will allow reuse of private addresses across network zones.

3.2 Sequence Numbers

IPoC uses two separate sequence numbers for upstream Interests and downstream Data objects. **Upstream Sequence Numbers (USNs)** are monotonically increasing integer values embedded in the Interest names. Since Interest messages may arrive out-of-order due to the use of multiple network paths, the Gateway uses USNs to make sure that upstream IP packets are sent out into the IP network in the proper order. Similarly, the data packets carry **Downstream Sequence Numbers (DSNs)**. However, unlike USNs, DSNs are not part of the name but embedded in the Data packet. In our implementation, both USN and DSNs are unsigned 32-bit integers.

3.3 IPoC Data Structures and Communication Model

Both the Client and the Gateway implement a **Resequencer** that fills any gaps in packet sequence by holding out-of-order packets until the missing packets arrive or a wait timer expires. The wait timer is dynamically adjusted based on the observed packet delay. In addition, the Gateway uses two FIFO queues associated with each Client, a **Client Interest Table (CIT)** and an ingress queue. The Gateway maintains the CIT to record the names of pending Interests. The CIT is different from the Pending Interest Table in NDN, in that it is a FIFO rather than an unordered list. The ingress queue buffers packets arriving from the IP network if there are no entries in the CIT.

In our communication model, the Client can send “upstream” packets any time by sending Interest messages. The Gateway, on the other hand, can only return “downstream” packets when it has a pending Interest in its CIT. Therefore, the Client and the Gateway need to work together to ensure that the Gateway receives sufficient number of Interests to support downstream communication, even

when user traffic patterns are highly asymmetric or when the Client does not receive any IP packets from the user applications.

To accomplish this, IPoC uses two values, **Interest Deficit Count (IDC)** maintained by the Client and **Interest Deficit Report (IDR)** signaled by the Gateway (in Data packets) to control the Interest sending rate. The Client increments its IDC every time it receives a Data packet and decrements it upon sending an Interest. An IDC value greater than zero indicates that the Client should send an additional Interest message, even if it has no IP packets to send. As a result, the Client typically sends an Interest for every Data packet it receives, thus maintaining a constant number of “in-flight Interests” (IFI). The IDR sent by the Gateway to the Client can take the values: +1 (request increase of IFI by 1), 0 (no change) or -1 (decrease IFI by 1). The client simply adds the IDR to IDC. The IDR is an unacknowledged message element and is an inherently unreliable communication. The small value of IDR ensures that the loss of an IDR message will not have a significant impact on IPoC’s performance.

In the interest of brevity, we omit much of the protocol details. We encourage the interested readers to look at our Internet Draft [27] for a comprehensive description. We implemented and tested the IPoC protocol using NDNsim [11] and the complete codebase is available on GitHub [22].

4 IPOC IN 5G NETWORKS

5G networks are expected to utilize multiple RF bands, with UEs using multiple simultaneous links in different bands and WiFi networks. It is also expected to have significantly more frequent handover events than current LTE networks [3]. Hence, the current approach to providing user plane mobility support via GTP tunnels may not be sufficient to address these two factors. Since ICN can natively support mobility through its data-centric design and stateful forwarding plane, the community has argued [16] [25] that an ICN solution for consumer mobility would be more appropriate. In addition to the benefits that may be present for native ICN applications, the use of IPoC can allow the network to leverage ICN as a mobility layer for IP user plane traffic.

In this section, we use TCP/IP application flows to compare IPoC over NDN with GTP and show that our protocol does not perform any worse than GTP. The second part of the study shows the promise of IPoC/NDN as an intelligent network layer that addresses

Figure 4: IPoC vs GTP Performance.

two shortcomings of LTE-EPC, burdensome handover behavior and the complexity of utilizing multiple links simultaneously.

4.1 IPoC vs GTP Performance

In this section, we compare the performance of IPoC to GTP tunnels used in LTE-EPC. We choose GTP since it is widely used in LTE-EPC network and therefore provides a good baseline for comparison. We use the topology from Fig. 2; the UE-eNodeB links have 100 Mbps bandwidth, and the rest are 40 Gbps. These match the currently deployed mobile networks, where the maximum average LTE throughput is approximately 50 Mbps [15]. The LTE-EPC topology is identical, with the Packet Data Gateway replacing the IPoC Gateway. Since an NDN stack for radio links does not exist, we used point-to-point links for these experiments. We focus on TCP/IP protocol performance and for expedience in simulation use 1400 byte MTU to accommodate IPoC and GTP overheads. We use NS-3 protocol stack for single file transfers and network simulation cradle (NSC) which provides better flow fairness for multi-file transfers. We only use the path through eNodeB1 for the experiments in this section and both paths for handover experiments in the next section. For this work, the simplistic topology is sufficient since we are only interested in IPoC/NDN performance between the UE and the Gateway. We plan to expand our work in future to include multiple Gateway and Clients.

4.1.1 Efficiency and Throughput. For investigating efficiency and throughput of IPoC, we transfer 100 files between the UE and the remote server under lossless conditions. These files are between 2KB and 200 MB and were drawn using a log-uniform distribution. For comparison, we assume GTP/UDP/IPv4 stack in the LTE core, which introduces 40 Bytes of overhead per user packet (GTP/UDP/IPv6 would be at least 60 Bytes).

We define protocol efficiency as the ratio of the cumulative size of IP packets to the total transmitted bytes on the UE-Gateway path. Fig. 3a compares IPoC and GTP efficiencies on the eNodeB-Gateway link for a single file transfer (upload and download numbers are identical). We observe that IPoC's downstream efficiency and upstream efficiencies were around 96% and 97%, respectively, while GTP's efficiency was 97.5%. We estimated GTP/UDP/IPv6 efficiency to be 96.4%. Thus, IPoC provides very similar core network efficiency to GTP.

Fig. 3b shows the goodput for a single file download using IPoC is 5% less than existing LTE-EPC (labeled "Pure IP") when transferring a large file. This happens since an IPoC tunnel terminates in the UE and the IPoC overhead is carried on the bottleneck UE-eNodeB link, whereas the GTP tunnel in LTE-EPC terminates in the eNodeB.

While IPoC's performance is slightly worse than Pure IP, we anticipate IPoC will take advantage of larger MTUs and NDN's per-hop fragmentation to boost the efficiency of downstream Data messages, which can carry an arbitrary number of IP packets. Previous works [1] [18] have suggested the use of hop-by-hop fragmentation within the layer-2 protocol as a way to allow much larger layer-3 MTUs than can be typically supported in IP networks that are usually limited to a 1500 byte lowest-common-denominator MTU in practice. Hop-by-hop fragmentation and reassembly would be expected to provide reliable delivery of nearly arbitrarily large NDN messages and is already supported by the NDN link layer protocol (NDNLPv2) stack for both Interest and Data messages.

4.1.2 Variance in Packet Delay. To understand the effect of the IFI on packet delay, we measure the Gateway-to-Client delay for each packet during a large file transfer. The inset in Fig. 3c shows that during the TCP slow-start, some IP packets took 20 to 30ms to reach the Client from the Gateway. In our IDR signaling protocol [27], the gateway keeps a small number of pending Interests in its CIT during idle periods, so when a large number of downstream packets arrive and consume the pending Interests, the rest of the IP packets must wait at the Gateway for the next Interest. Fig. 3c indicates that Interest starvation affects some packets in the slow-start, but IPoC very quickly ramps up the IFI to the appropriate level until the link is saturated.

4.1.3 Fairness. To demonstrate IPoC does not affect TCP flow fairness, we perform ten simultaneous unidirectional transfers using small (1MB), medium (10MB) and large (100MB and 200MB) files. The small standard deviations represented by the error bars in Fig. 4a illustrate that IPoC maintains TCP's flow fairness regardless of the flow size. The minor difference between IPoC and GTP (labeled "Pure IP") completion times is the result of IPoC overhead on the radio link as we previously discussed.

Figure 5: LTE [9] vs NDN/IPoC handover scenarios.

4.1.4 Return Channel Overhead. TCP/IP flows commonly generate a return channel overhead (TCP ACK stream) that equates to approximately 2% of the forward channel data rate. These ACK packets are small packets, which in IPoC are additionally encumbered by the IPoC/NDN header, increasing their size (and hence the overhead). We measured this return channel overhead for TCP uploads and downloads, both with pure IP and with IPoC/NDN for a range of file sizes. As Fig. 4c shows, the overhead for IP is about 2% for large file sizes, as compared to 4-6% overhead for IPoC/NDN. With smaller file sizes, both approaches become less efficient due to TCP SYN/FIN handshaking.

4.1.5 Throughput and Delay on Lossy Links. For some protocols like TCP, packet loss dramatically reduces application throughput. To ensure we do not introduce any additional adverse effects, we perform file transfers with a lossy bottleneck link without layer 2 or 3 retransmissions. We transfer ten files for each simulation ranging from 2KB to 200MB with wait times between transfers following a uniform distribution between 10ms to 10 seconds.

Fig. 4b shows average TCP throughput drops in both EPC (“IP”) and IPoC cases as packet loss rate increases from 10^{-7} to 10^{-3} ,

as expected. At higher loss rates (10^{-5} to 10^{-3}) the difference between IPoC and EPC disappears since TCP is unable to saturate the bottleneck link.

In this section, we have demonstrated that IPoC has all the desirable characteristics for real-world deployments. Its core network efficiency is equivalent to LTE-EPC, its radio link efficiency is only slightly less than with EPC (and would improve with per-hop fragmentation), it does not introduce any significant packet delay that would impact applications, and it treats all flows fairly. Having established that IPoC can maintain the current level of network performance, we now demonstrate its potential to simplify and improve 5G mobile networks.

4.2 Handover with IPoC/NDN

In mobile communication, a handover happens when an ongoing data or voice session is moved from one base station (source eNodeB) to another (destination eNodeB), typically as a result of UE motion. During handover, the source eNodeB drives existing communications, coordinates with the destination eNodeB, queues in-flight packets and creates a temporary (X2) tunnel to the destination eNodeB leading to additional protocol complexity, path length, and latency. In comparison, IPoC/NDN based handover protocol can be more straightforward.

In this work, we propose **two** NDN based handover protocols in Fig. 5, **Hard Handover** and **Soft Handover**. In our protocol, the UE, not the eNodeB, makes the handover decision. It first requests authorization from the mobility manager (MME). Once authorized, the UE sets up a new channel to a new eNodeB and starts sending Interest packets. In hard handover, when the new link is established, the UE retransmits all pending Interests on the new link. These retransmitted Interests establish a forwarding path for the corresponding Data packets that have not yet been sent by the Gateway, and retrieve from the Gateway cache or an in-network cache those that have. A key design assumption for our protocol is the Gateway and in-network caches will have enough capacity to support the expected handover durations.

In soft handover (or “make-before-break”), we assume communication over the old channel is still possible while the UE sets up a new channel to a new eNodeB. In-flight packets continue to use the old channel while all new Interests take the new path. Once all in-flight packets are received, i.e., all Pending Interests are satisfied, the UE detaches from the old path. Since there is no retransmission of Interests involved, this approach is more straightforward, more efficient, and higher performance than hard handover. Note that soft handover is only possible if the UE can support two radio channels simultaneously, a feature expected on 5G UEs.

Fig. 5 compares protocol complexity of our NDN based handover protocols with the current LTE-EPC handover protocol and shows that IPoC/NDN can make mobile handover much simpler. In the next section, we evaluate our handover protocols in terms of latency, throughput and packet loss.

In the following sections, we evaluate our handover protocols in terms of packet latency and application throughput. We do not compare IPoC/NDN with TCP/IP since other works have already evaluated TCP/IP performance during handover [13] [9]. Using the topology described in Section 4.1, we download a 100MB file over

Figure 6: IPoC/NDN performance during handover.

TCP and three seconds into the transfer, schedule a handover from eNodeB1 to eNodeB2. In the hard-handover scenario, we assume the underlying radio channel setup takes the maximum delay allowed in LTE specification, 65ms [9].

4.2.1 Packet latency during handover. Fig. 6a shows the packet latency between the IPoC Gateway and the Client. Handshake and TCP connection setup contribute to a higher delay at the beginning, then the packet latency settles into a value equal to the baseline Gateway-Client delay (10ms) plus the bottleneck link buffer delay (15ms). During hard handover, the delay temporarily increases by 85ms; 65 ms for radio channel setup and 20ms (UE-Gateway RTT) to bring back data over the new link. If Data packets were cached in-network rather than at the Gateway, this value would decrease accordingly. Packet latency during soft handover does not increase. In fact, packet latency drops temporarily since the bottleneck link buffer in the new link is empty prior to handover. During hard handover, the throughput decreases as each of the retransmitted packets are delayed by one RTT. However, the drop is momentary, and TCP congestion window is not affected. Fig. 6b corroborates these observations; during hard handover, TCP throughput decreases momentarily but recovers quickly. By comparison, we notice an increase in throughput during soft handover due to the temporary simultaneous use of both links.

For hard handover, the resequencer timeout and cache duration are essential. Packet loss will occur if the resequencer declares packets as “lost” before the retransmitted Interests can bring back data. However, a large timeout value means out-of-sequence packets will need to wait longer. Therefore, the trade-off between delaying a few out-of-order packets vs. triggering network (e.g., TCP) or application layer packet retransmissions should be carefully considered.

4.3 Dual Connectivity using NDN

A new technology called Dual-Connectivity allows an LTE UE to connect to two eNodeBs simultaneously. While this increases the total bandwidth available to a mobile device, complex protocols in the network are required to keep the data routing transparent to the end device. It is expected that 5G handsets would have several radio antennas allowing them to connect to different cell towers, micro-cells, and WiFi access points at the same time. The ability

to use multiple links at the same time can improve throughput and allow the network operators to deliver differentiated services over appropriate channels. To demonstrate how NDN can help with this scenario, we deployed a simple NDN round-robin strategy with IPoC over two mobile links. Fig. 6c shows that our simple strategy could simultaneously utilize both links and the goodput doubled. While further study is needed to establish effective Interest transmission strategies to optimally utilize links of disparate and time-varying capacity, we expect sophisticated NDN strategies will be able to utilize multiple WiFi and 5G radio links simultaneously.

These two scenarios demonstrate IPoC/NDN’s promise in the 5G network layer for reducing network complexity and introducing intelligent features.

5 CONCLUSIONS AND FUTURE WORK

In this work, we propose IPoC, a protocol that can enable a transition to ICN in mobile networks by encapsulating and forwarding IP traffic over an ICN core. IPoC allows existing applications to keep using IP until they are ready to transition into native use of ICN. We show that IPoC imposes very little additional overhead and does not degrade application performance. In addition to addressing the deployment question, we show that IPoC/NDN can also benefit 5G mobile networks by simplifying handover operations and introducing intelligent multi-path strategies. The codebase for this work is open-source and is available on GitHub [22].

While our initial simulations present promising news, several future aspects remain to be addressed. We plan to investigate IPoC’s performance with a more complex network topology with multiple Clients and Gateways. We plan to fine-tune our protocol by evaluating it in application scenarios other than mobile networks. We also plan to investigate IPoC/NDN for other aspects of 5G networks such as utilizing links with different capacity, supporting WiFi and 5G radio links simultaneously, and device to device communication.

6 ACKNOWLEDGMENTS

We thank Christos Papadopoulos, Tetsuya Nakamura, and anonymous reviewers for their comments and feedback and Greg Rutz for his initial CCN-based implementation.

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