

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 paradigm that addresses content directly rather than addressing end-hosts. An ICN-based networking layer aligns better with application needs by providing content-centric security, in-network caching, and intelligent packet forwarding making it useful to both users and service providers alike. However, transitioning to an ICN-only networking paradigm 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.

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.

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 ranging from large data applications [9] [12] to building automation systems [11] and from vehicular networks [5] to IoT applications [3]. ICN can also simplify existing applications and networks; for example, the handover of a mobile device to a new base station currently requires packet queuing, path setup, and transitioning existing packet flows to the new path. On the contrary, a device utilizing ICN can simply start forwarding packets as soon as a new link comes up.

Despite the advantages, application compatibility is a significant hurdle that stands in the way of deploying an ICN-only network. Existing IP applications are constrained to use only IP networks and unable to utilize ICN networks.

We could address this obstacle by requiring that all IP applications be rewritten to use ICN natively, a tall order in a world with millions of connected applications. A hybrid network with dual-stack IP and ICN routers could also solve the problem [16] but adds cost and complexity.

In this paper, 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. IPoC can be implemented using either the NDN protocol or the CCN protocol; for this work, we use NDN primitives for our prototype implementation. Our protocol is also generic compared to the previous works on ICN tunneling [10] [13] [7] and works for any IP based communication. Using LTE Evolved Packet Core (LTE-EPC) in mobile networks as the driving example, we show that IPoC over NDN (IPoC/NDN) can potentially provide an intelligent network layer for 5G networks.

This paper has two distinct sections. The first part discusses IPoC protocol details and compares IPoC's performance with the GPRS Tunneling Protocol (GTP) used in LTE-EPC. We show that IPoC/NDN is capable of supporting the current level of network performance. The second part demonstrates that by leveraging the elegant, built-in 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 [14] and intelligent handover that are currently difficult to implement with 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. [13] proposed an architecture that enables IP applications to communicate with a ICN network core ICN using a Network Attachment Point (NAP) that interprets each IP based protocol. Similarly, Refaei et al. [10] proposed a general purpose, extensible IP-to-NDN gateway that translates between NDN and IP packets based on pre-defined rules. Interpreting each 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, our protocol simply transports IP packets across an

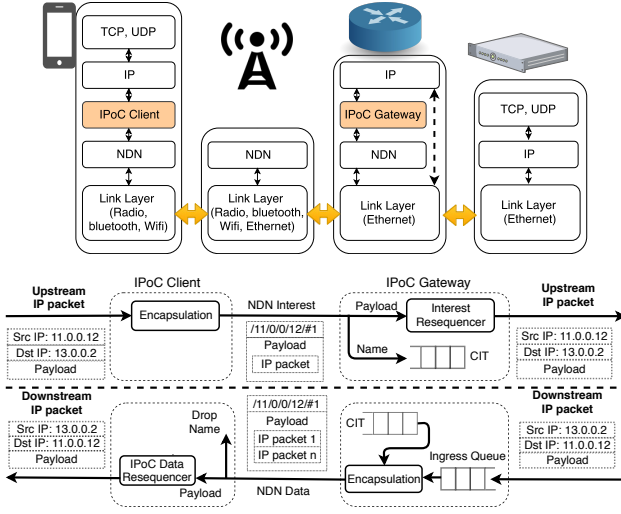


Figure 1: IP packet paths in IPoC.

ICN network, without the need for interrupting end-to-end communication between the endpoint applications.

Moiseenko et al. proposed TCP/ICN [7], 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, etc. In contrast, our protocol is generic and capable of carrying any IP traffic without protocol specific modifications.

Wu et al. investigated the issues for incrementally deploying NDN in LANs [16] using dual-stack switches that can support both NDN and IP protocols. While the Dual-Stack devices help with NDN deployment, they do not provide enhanced network support for current applications. On the contrary, our approach has the potential to simplify existing protocols and improve application performance.

3 THE IPOC PROTOCOL

In this section, we discuss the important constructs of the IPoC protocol. Figure 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.

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 (Figure 1). 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.

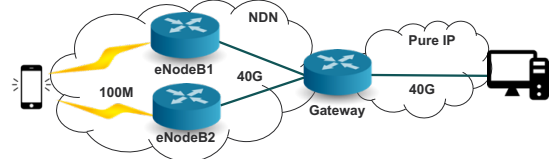


Figure 2: Evaluation topology.

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 [1], 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.

Our implementation uses hierarchical names between the Client and the Gateway with the following naming convention: `/IPoC/<hex_ipaddr>/<b64_seq>`. For this study, **IPoC** is the reserved name prefix that we use in all IPoC messages. **hex_ipaddr** represents an IP address encoded as a hexadecimal string, e.g., 11.0.0.12 translates to "0b/00/00/0c" (Figure 1 uses decimal octets for clarity). **b64_seq** is a base64-encoded Upstream Sequence Number.

Since subsequent packets can use different paths between the Gateway and the UE, IPoC uses Upstream Sequence Numbers (**USNs**) and Downstream Sequence Numbers (**DSNs**) to ensure proper ordering of the Interest and Data packet payloads. Both the Client and the Gateway implement a **Re-sequencer** 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.

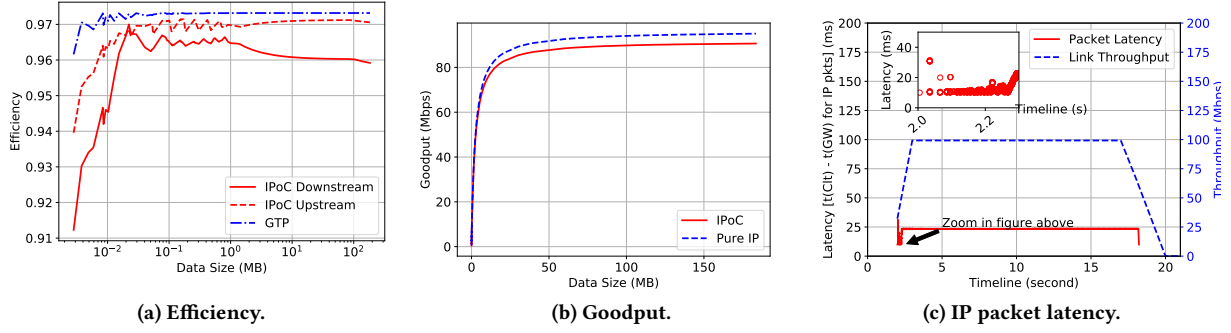


Figure 3: IPoC performance evaluation for single file transfer.

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 IDR message will not have a significant impact on performance.

In the interest of brevity, we omit much of the protocol details. We encourage the reader to look at our Internet Draft [15] for a comprehensive description of the protocol.

3.1 IPoC vs GTP Performance

In this section, we compare the performance of IPoC to GTP tunnels used in LTE-EPC. We use the topology from Figure 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 [2]. 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 topology to include multiple Gateway and Clients in future work.

3.1.1 Efficiency and Throughput. For investigating efficiency and throughput of IPoC, we transfer 100 files between the UE and the remote server. These files are between 2KB and 200 MB and were drawn from 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. Figure 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. In real systems, we anticipate IPoC taking advantage of larger MTUs as well as per-hop fragmentation to further boost efficiency.

Figure 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 the

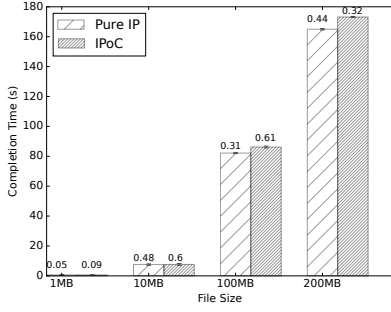


Figure 4: Flow completion time and fairness.

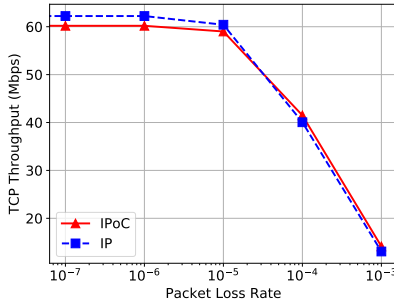


Figure 5: Average TCP throughput.

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.

3.1.2 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 Figure 3c shows that as the TCP connection begins slow-start, some IP packets took 20 to 30ms to reach the Client from the Gateway. In our IDR signaling protocol [15], 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. Figure 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.

3.1.3 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 Figure 4 illustrate that IPoC maintains TCP's flow fairness regardless of the flow size. The minor

difference between IPoC and EPC (labeled "Pure IP") completion times is the result of IPoC overhead on the radio link as discussed previously.

3.1.4 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.

Figure 5 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 can not saturate the bottleneck link.

In this section, we have demonstrated that IPoC has 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 IPOC/NDN IN 5G NETWORKS

5G networks are expected to utilize multiple RF bands, with UEs using multiple simultaneous links in different bands and significantly more handover events than we currently see in LTE networks [4]. In this section, we show the promise of IPoC as an intelligent network layer that addresses two shortcomings of LTE-EPC, burdensome handover behavior and the complexity of utilizing multiple links simultaneously.

4.1 Handover with IPoC/NDN

In mobile communication, a handover happens when an ongoing data or voice session is moved from one base station (src. eNodeB) to another (dst. eNodeB), typically as a result of UE motion. During handover, the src. eNodeB drives existing communications, coordinates with the dst. eNodeB, queues in-flight packets and creates a temporary (X2) tunnel to the dst. 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 Figure 7, **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

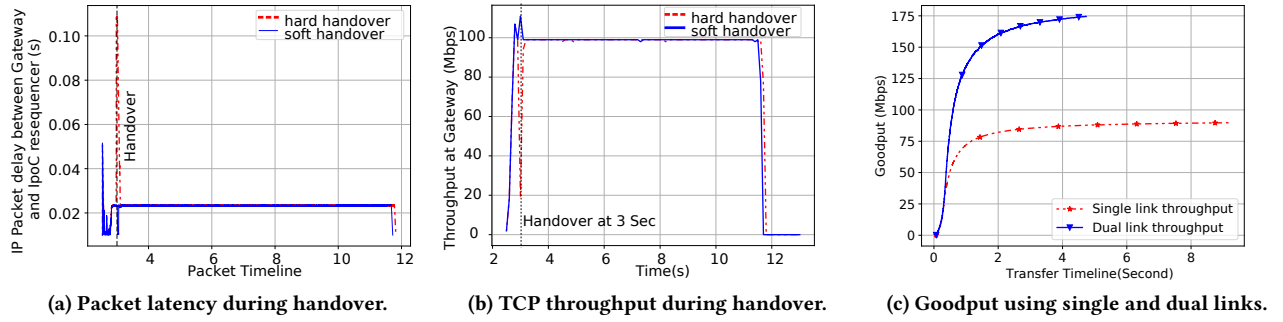


Figure 6: IPoC/NDN performance during handover.

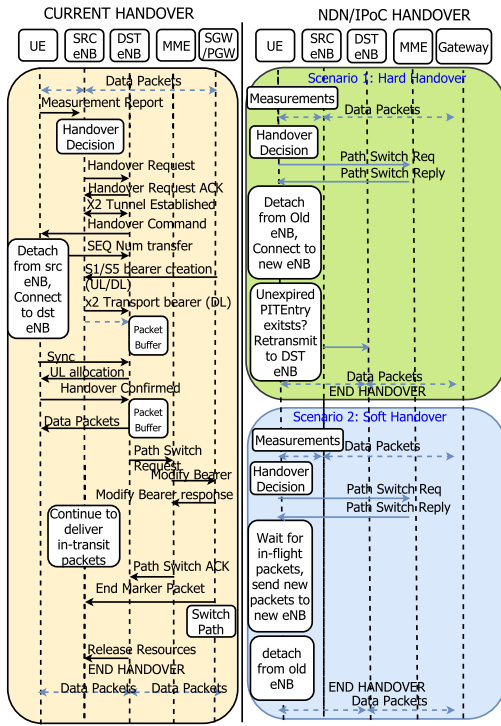


Figure 7: LTE [6] vs IPoC handover scenarios.

channel to a new eNodeB and simply starts sending Interest packets. In hard handover, when the new link is established, the UE retransmits all pending Interests on the new link. These resent 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 simply detaches from the old path. Since there is no retransmission of Interests involved, this approach is simpler, 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.

Figure 7 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.

4.2 IPoC/NDN Handover Performance

In this section, we evaluate our handover protocol's performance. We do not compare IPoC/NDN with TCP/IP since other works have already evaluated TCP/IP performance during handover [8] [6]. Using the topology described in Section 3.1, we download a 100MB file over 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 [6].

4.2.1 Packet latency during handover. Figure 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. Figure 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 important. Packet loss will occur if the resequencer declares packets as "lost" before the retransmitted Interests can bring back data. However, a large resequencer timeout value means out-of-sequence packets will need to wait longer; 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. We deployed a simple NDN round-robin strategy with IPoC over two mobile links. Figure 6c shows that our simple strategy could simultaneously utilize both links and the goodput doubled. Further study is needed to establish effective Interest transmission strategies to optimally utilize links of disparate and time-varying capacity.

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 goodput. In addition, we show that IPoC/NDN can also benefit 5G mobile networks by simplifying handover operations and introducing intelligent multi-path strategies.

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 are interested in investigating IPoC/NDN for other aspects of 5G networks such as utilizing links with different amounts of

bandwidth and supporting WiFi and mobile networks simultaneously. Finally, we plan to fine-tune our protocol by evaluating it in application scenarios other than mobile networks.

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