IC-MCN: An Architecture for an Information-Centric Mobile Converged Network

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Abstract

Rapid increases in bandwidth-intensive communications on mobile devices is challenging the Internet's scalability. *Mobile converged networking*, with its three-fold convergence of technology, service, and network is receiving significant attention as a potential solution to this problem. Unfortunately, proposed mobile convergence approaches are limited by the prevailing Internet Protocol (IP)-based Internet infrastructure. The inherently host-centric IP lacks scalability to accommodate an explosion in multimedia content traffic, especially in the context of mobile convergence. Information-centric networking (ICN), a new networking paradigm, has been proposed to overcome IP's scalability problems. By routing requests and data using content names instead of host addresses, ICN enables the exploitation of in-network caching, multi-homing, and multiple radio technologies (multi-RAT), and avoids the restrictions of a host-centric foundation. We believe that ICN can play a central role in a mobile converged network.

We use Named Data Networking (NDN), a popular ICN architecture, as the foundation for a novel information-centric mobile converged network (IC-MCN). Our architecture allows different networks, multiple interfaces, and in-network caching to all be leveraged effectively by mobile devices. We discuss the details of the architecture, identify its advantages, and explore open challenges to the creation of a practical IC-MCN for the future.

1 Introduction

Today, 54% of worldwide Internet traffic originates from mobile devices, and this proportion is growing (Ref: Cisco Visual Networking Index, 2016). Mobile devices (or mobiles) are becoming more sophisticated coming equipped with multiple communication interfaces, such as cellular, WiFi, Bluetooth, and WiMax. Applications such as Skype and FaceTime are replacing traditional cellular voice services, while streaming services such as Netflix and YouTube are becoming more popular, driving the Internet and the cellular backbones to their limits.

Scalability concerns have motivated a search for new approaches to meet these growing demands. The *mobile converged network* (MCN), with its three-fold convergence of technology, services, and network [1], is one of these approaches. Technology convergence enables the simultaneous usage of multiple communication technologies, while service convergence allows each service to be accessed from any device, and network convergence integrates the infrastructure and management of both broadband and Telecom networks. An MCN will allow mobiles to *converge* multiple communication technologies and perform coordinated communication, e.g., allowing seamless data transfer across diverse infrastructure such as broadband, wireless, and satellite. It would scale to accommodate next-generation applications while maintaining support for the current best-effort, video-on-demand (VoD), and videoconferencing services.

In the literature, Internet Protocol (IP) has been proposed as the foundation of a converged network [1]. But, the *host-centric* networking paradigm enforced by IP scales poorly. Proposals for a scalable future Internet are rallying around the *information-centric* networking (ICN) paradigm [2, 3]. ICN allows data to be addressed by name, leverages pervasive in-network caching, and provides better scalability. We believe that a truly scalable MCN should follow these principles.

In this article, we study the design choices of an information-centric mobile converged network (IC-MCN) and propose a novel IC-MCN architecture. We *(i)* illustrate how the intrinsic properties of ICN will help improve mobile users' quality of experience (QoE) and help satisfy throughput demands; *(ii)* discuss how multi-RAT can be leveraged by the mobiles and the intermediate routers; and *(iii)* also discuss content classification and services differentiation, which are crucial concepts for convergence. We extend the popular Named Data Networking (NDN) architecture [4] to propose our IC-MCN architecture. NDN is especially amenable to addressing the two major challenges of mobile networks: high bandwidth requirements and high node mobility.

In what follows, we review the ICN paradigm and the NDN architecture. Then, we illustrate the design of the NDN-based IC-MCN. Finally, we investigate open challenges for an ICN-based MCN and conclude with some experimental insights on multi-RAT utilization.

2 Overview of Information-Centric Networking

Various ICN architectures have been proposed, such as named-data networking (CCN/NDN) [4], Publish/Subscribe Internet Routing Paradigm [5, 6], and Data-Oriented Network Architecture [3]. We refer the readers to [2] for a survey of these architectures. Although they differ in design, all these architectures employ ICN fundamentals such as named data, name-based routing, and in-network caching. Of the proposed architectures, NDN (and the related CCN) has become popular as it is amenable for Internet-wide deployment with limited infrastructural change. In this article, we extend the NDN architecture while noting that all proposed architectures are nascent and have their inherent challenges [7].

[Figure 1 about here.]

The NDN network stack is illustrated in Figure 1 [4]. In NDN, the content objects are broken into chunks by the content provider. Each content chunk is requested by name, using an interest message (a request containing the chunk name). The interest is generated at the application layer, which is also responsible for security and privacy functionalities. The second layer of the stack abstracts NDN from the underlying network; TCP, UDP, and IP transports are supported here for ease of implementation, but a pure NDN network is also possible. The strategy layer makes intelligent forwarding decisions, and can be customized for application in MCN.

Every NDN router utilizes three primary data structures, namely the Forwarding Information Base (FIB), Content Store (CS), and Pending Interest Table (PIT). The FIB

(Ref. Figure 1) is similar to an IP routing table, facilitating the selection of interfaces (or simply *faces*, in NDN nomenclature) on which an interest should be forwarded. The CS is a content cache, allowing interests to be satisfied by intermediate routers. The PIT maps unsatisfied interests the interfaces on which they were received, allowing the corresponding content chunks to be forwarded to the correct destinations.

Naming conventions are critical in NDN, as content names are used in searching, routing, and data delivery. Names are generally hierarchical, and each content object has a unique identifier; sequence numbers are appended to content names to make each chunk independently addressable.

3 IC-MCN: Information-Centric Mobile Converged Network Architecture

Now we discuss how to integrate the NDN architecture with the MCN concept to create an IC-MCN architecture. The architecture enables mobile convergence in two fundamental ways: *(a)* Enabling simultaneous use of multiple interfaces by a device, thus speeding up content access to improve quality of service (QoS) and quality of experience (QoE). We also avoid the mobility issues inherent to TCP, wherein a change in interface or AP would require a session tear-down and re-establishment. *(b)* Reducing download time with the use of in-network caching, placing desired content closer to the requesting mobiles and considerably reducing core network traffic, thus improving network scalability.

3.1 Network Setup and User Connectivity

Figure 2 illustrates the IC-MCN architecture, integrates the backbones of the Internet and cellular networks. The ICN Internet and the ICN cellular core will together be used for voice and data communication. All elements of this backbone will be equipped with name-based routing and content caching. Voice data would still be predominantly transferred over the cellular network, which supports bandwidth reservation. The Internet will be used to offload other types of data, as it provides much higher bandwidth.

A mobile device will have several interfaces (e.g., WiFi, WiMAX, ZigBee, etc.) available for simultaneous communications. The node within the purple circle in Figure 2 has Bluetooth (connecting to an ad-hoc network), WiMAX, WiFi, and cellular interfaces available for simultaneous use. The node uses the GSM/CDMA cellular network for voice service, and accesses the ICN Internet through an LTE interface connected to the Evolved Packet Core (EPC).

We propose caching content at the Serving and Packet Data Network (PDN) Gateways (GWs) in the EPC. Several eNodeBs (evolved Node Bs, or base stations) connected to a Serving GW can benefit from its cached content. With multi-RAT support in the EPC, a mobile connected to a PDN GW via another access technology (e.g., WLAN) can still benefit from the cached content in the PDN. The Mobility Management Entity (MME) in the EPC performs user tracking and user-to-network session handling and can use machine learning to predict the trajectory of mobiles. It can convey these predictions to the Serving GW, which in turn can redirect residual communications to the mobile through its current eNodeB. This improves the user's QoE by making content retrieval seamless during mobility.

Though mobility in the cellular network is handled intrinsically, mobility in the Internet is more challenging. ICN makes mobility seamless from a consumer's perspective; it can simply retransmit interests after a mobility event in order to continue retrieving a content object. However, the original interest sent prior to the consumer's relocation may still be satisfied along the original path. This could arguably be considered a waste of bandwidth, however in-network caching can negate this effect. In-network caching makes it unlikely that requests for popular content will even reach the core of the network; thus, load is concentrated at the edge. Even in cases where the interest is not satisfied at the network edge, the post-mobility interest can potentially be satisfied by a cache which was populated as a result of the original interest; furthermore, other consumers in both localities will be able to benefit from the cached content in the future. Additional detail about the mobility advantages of ICN can be found in [7].

[Figure 2 about here.]

3.2 Exploiting Multi-Technology For Communication

In IP networks, sessions are fixed to a particular IP address. As different interfaces need different IP addresses, it becomes difficult to leverage multiple interfaces to parallelize the retrieval of a single content. In NDN, a content is divided into independently-addressable chunks, and each chunk is obtained by sending a separate interest. In IC-MCN, interests for multiple chunks of a content object can be transmitted simultaneously, utilizing each interface.

In IC-MCN there are two types of multihoming: content multihoming and host multihoming. The ICN paradigm promotes content multihoming through pervasive caching. The advantages of content multihoming are twofold: first, the content can be cached closer to the user, reducing latency. Second, content can be available in multiple locations, which can be utilized concurrently to speed up downloads. In conjunction with multi-RAT communication, content multihoming can reduce content download times, as we will show in Section 5.

Host multihoming has significant bearing on a device's efficiency. A mobile device can identify the best interfaces (or communication technologies) to use concurrently to retrieve content, thus reducing download time and conserving battery life.

This identification can be performed by collecting statistics and making intelligent decisions in the strategy layer. The strategy can collect statistics such as latency on its own accord, and also receive feedback on loss rates and channel conditions from the application and physical layers, respectively. Also, devices can use historical data driven learning algorithms to order interfaces in terms of performance. Note that simultaneously optimizing for cost reduction and cache utilization is difficult. This optimization problem easily becomes intractable, necessitating the development of fast heuristics. The right running period of the algorithm would depend on the trade-off of the energy it consumes versus its energy benefits. The strategy layer of a requesting mobile can be used to enforce strategies such as *TransmitOnAll* interfaces, *SelectTheBest* interface, and *ProportionallyTransmit* on each interface, depending on configuration parameters and observations. Intermediate routers can also use this technique if they have multiple viable interfaces for forwarding a particular interest.

[Figure 3 about here.]

Figure 3 illustrates a possible result from an optimizing strategy layer: 35% of interests are transmitted on the ad-hoc interface (**F4**), 30% are transmitted on the WiMax interface (**F2**), 25% are transmitted on the WiFi interface (**F1**), and the remaining 10% on the cellular interface (**F3**). In this example, the ad-hoc neighbor has a significant portion of the content cached, but the interface has low bandwidth; hence, the WiFi, WiMAX, and cellular links are used to speed up the download. The WiFi and WiMAX links are favored on account of higher bandwidth and signal strength.

In essence, the IC-MCN architecture helps combine content and host multihoming: availability of a content in several caches enhances its accessibility and improves both QoS and QoE. For instance, a mobile, that is retrieving a content over cellular and WiFi interfaces, might move outside of the WiFi coverage, in which case the strategy can strategy layer can increase use of the cellular interface until WiFi connectivity is reestablished.

3.3 Content and Service Differentiation

Today's users are immersed in on-line gaming, audio/video streaming, web browsing, and video chatting on their mobile devices. Multimedia traffic, with requirements of high bandwidth and low latency, now constitutes the majority of Internet traffic. Interestingly, the majority of the requested multimedia contents are useful for many users; in fact, a small proportion of content objects (around 20%) make up more than 80% of the requests (as content popularity follows a power-law distribution) [8]. The remaining 20% of traffic is generally non-multimedia or one-to-one real-time traffic; as this is a small portion of the overall load, it does not affect network scalability. These trends motivate us to classify content in order to improve QoS.

3.3.1 Content Differentiation Motivated by Caching

We divide contents on the IC-MCN into two major classes, namely **cacheable** and **non-cacheable**.

Cacheable content, as the name implies, can potentially be cached by each node in the network. Cacheable content can be further sub-classified as:

- *Globally popular*: Several content objects are globally popular (e.g., trending YouTube videos) and would likely be cached in all edge routers.
- *Geographically popular*: Some content objects are popular in isolated regions (e.g., a game of badminton played in China or a cricket match in India), thus necessitating localized caching.
- *Temporally popular*: Content objects such as live streams of a game, which although popular become unusable after an expiry time.

Non-cacheable content: is potentially unpopular (e.g., a movie dubbed in a minority language); is useful for only an individual or small group (e.g., emails, video chats, etc.); or are one-to-one encrypted communications (e.g., online banking). These data are not popular, and thus caching them does not help reduce network load. Fortunately, these contents make up only a small fraction of the requests and hence do not need special attention in an IC-MCN.

In the information-centric paradigm, all network elements can, collaboratively or independently, cache content objects. Caching can happen at core routers; at the content delivery nodes (e.g., Akamai, EdgeCast, etc.) throughout the ISPs; at the network-edge routers, proxies, and access points; and also on individual devices (especially for ad-hoc communication). In-network caching causes an *inversion effect*–the majority of the popular content objects are gradually pushed closer to end users, while the network-core mostly stores less popular data.

Thus far, caching has been neglected in telecommunication networks, but is now featured in the proposed 5G standard. In current 3G/4G networks, users cannot benefit from in-network caching of the ICN architecture unless it comes to be supported by network infrastructure, such as base stations and telecommunication switches. Caching policies should be customized for the telecommunication network.; for instance, base stations can cache content objects with smaller sizes and high popularity, while internal switches cache larger, less popular multimedia objects.

Effective in-network caching is extremely important for an IC-MCN to handle future traffic growth. Wang *et al.* show that optimal cache placement depends on many factors, such as topology, popularity distribution, and network size [9]. However, there remains a need for more research on effective cache placement and replacement strategies.

3.3.2 Service Differentiation Motivated by Content Type

Service differentiation is necessary to meet the varied requirements for different types of content requests. Generally, traffic on an MCN can be divided into five main categories: voice, VoD, real-time video streaming, interactive applications, and best-effort. These service requirements can be further refined based on the needs of each application (e.g., the MPEG I-frame has higher priority compared to P/B frames).

In an IC-MCN, more effective differentiation can be applied than in IP networks (which implement Integrated Services and Differentiated Services in Layer 3). For instance, NDN allows content objects to pass through the strategy layer, facilitating adaptation of caching and forwarding strategies to changing network conditions. Since flows can be identified by name, routers can maintain statistics for each in order to maintain individual statistics and provide customized service to each flow; this can be effective even if NDN is implemented on top of an IP stack utilizing differentiated services, which aggregates all flows.

We speculate that adding cross-layer optimization to an NDN forwarding strategy would help facilitate enhanced per-flow QoS, and in turn improve QoE for the end users. In addition, content priority can be leveraged in making caching decisions, in order to improve overall network efficiency.

4 Open Challenges

We have illustrated how a scalable information-centric mobile converged network can be created using an ICN architecture. However, several open challenges need to be addressed to transition from theory to practice, we discuss them here.

- ***Interference from Multiple Interfaces:*** With ICN a mobile user can benefit from multi-RAT and multihoming, until now unprecedented in communication. More specifically, for the large contents (e.g., HD movies), the user can divide the interests into different interest groups, each group being assigned to a particular interface (e.g., WiFi, WiMax, cellular). All mobiles in the network can simultaneously use this functionality, thus overloading the available wireless spectrum (either 2.4 GHz or 5 GHz). Given the paucity of channels, this simultaneous use of multiple interfaces may significantly increase co-channel and inter-channel interferences, undermining communication efficiency. There are approaches that utilize software-defined, multiple-input-multiple-output, and cognitive radios, which increase the possibility of simultaneous wireless communications. However, those solutions generally require spatial, time-division, or spatial time-division multiple access techniques, which are currently not scalable for large multi-interface networks [10].

- ***Effective Caching and Cache Replacement Strategies:*** A significant facet of ICN is in-network caching, which still has several challenges. Despite solid-state memory becoming less expensive, all devices in the network cannot be provisioned with caches immediately. Thus effective cache placement/replacement strategies have to be employed. In the IC-MCN, use of pervasive caching, massive amounts of content, availability of multiple interfaces, and potentially high device mobility (both the providers and the consumers) make the problem more intractable. Proposed cooperative caching techniques, which work well in the wireless ad-hoc setting may not scale in an IC-MCN. On the other hand, non-cooperative caching may result in sub-optimal network performance. In addition, the cache replacement strategies also need reconsideration.

  On another note, although the end-user caching is beneficial, yet a caching device needs to dedicate a portion of its battery-energy for the sake of requests from other users. Hence incentive mechanisms need to be devised to incentivize the users to open up their devices as cache for their neighbors. This is an interesting direction of study that is relatively unexplored.

- ***Security and Privacy:*** These two aspects are important concerns in every new architecture. In the ICN paradigm self-certified signatures allow the data publisher (or content provider) to guarantee data provenance and security. End-users can validate the origin of each content chunk using its signature. The same mechanism can be used to validate data integrity. On the other hand, the use of names to identify interests enables user identification and censorship. A forwarding node (e.g., base-station, proxy, switch, or router) within the first hop of a user can monitor its request history by associating the requested content names to the individual user. This will allow the routers to monitor, identify, and censor users, which is undesirable; avoidance of such monitoring is challenging, but some solutions have been proposed [11].

  Moreover, mechanisms have to be proposed for data access control. The data may be cached close to the users, however mechanisms need to be developed to allow only legitimate users to access controlled data. Recently, we proposed a mechanism to address this problem [12]. But, more needs to be done – we refer interested readers to a survey in ICN security, privacy, and access control [13].

- ***Network Effectiveness in the Face of Mobility:*** NDN inherently tackles consumer mobility by dividing content into small, independently named chunks and making the communication receiver-driven. A mobile client can obtain outstanding content chunks at its new location by re-sending the interests towards the provider.

Though the original outstanding interest may still be satisfied, the content object can potentially be used to satisfy the retransmitted interest or the interests of other consumers. In IC-MCN with the caching in the Service and PDN GWs and the interaction between the Service GW and the MMU to redirect requested chunks, QoS/QoE can be improved and bandwidth wastage curtailed.

  On the other hand, provider mobility is a big open challenge. Content providers such as Netflix may not move their servers' locations. However, in the Internet of tomorrow, each mobile device can become a provider. The question then is, how is the network going to know where the provider is? Popular content may be stored in intermediate nodes in high likelihood, thus needing the provider itself to satisfy few requests. But this is not true for all types of content (e.g., non-cacheable or multi-version content). Provider mobility will increase data request failures (to the previous location(s)), route failures, and route churns, thus impacting overall network performance. Thus, it is imperative that the impact of provider mobility be addressed.

- ***Migration from Telecom Network to Datacom Network*:** At last, we wonder if it is possible to entirely eliminate the core cellular network from the picture and serve all users' expectations through data communication. With the advent of the 4G/LTE technologies the bulk of data communication is happening over the data communication network (Internet). Despite the current shift from Telecom to Datacom oriented services, quality of service, specifically for voice call, is still a legitimate concern, which prevents complete migration from the telecommunication network to an all-data communication network (a challenge being explored in 5G). This migration will integrate all communications in the Internet and augment network convergence, resulting in one technology that receives all investment and innovative attention. The challenge is, how can this be done?

5 Multi-RAT Forwarding Strategy: Experimental Insights

To study the improvement from using multi-RAT in IC-MCN, we designed a basic forwarding strategy to enable a mobile to use multiple interfaces. The strategy weighs faces based on their observed latency and loss characteristics. For each face, an exponentially-weighted moving average (EWMA) of round-trip latencies, as well as an EWMA over a boolean timeout metric (timed-out is 1 and satisfied is 0) is maintained. The coefficients of the latency and loss EWMAs are $0 \leq \alpha, \beta \leq 1$ respectively. The cost $c(f_i)$ of face f_i is a weighted sum of the normalized latency (latency of face/maximum latency of all faces) and normalized timeout on that face (with the weight $0 \leq \gamma \leq 1$ for normalized latency and $(1 - \gamma)$ for timeout). The weight w_i of f_i is $1 - cost(f_i)$; we divide the chunk requests proportionally among the faces based on their weights.

We implemented our strategy in ndnSIM (an NDN module running in ns-3) and compared it against two other strategies: all faces chosen with equal probability (Rand), and a fixed face always chosen. We performed our evaluation on a 9-node representative topology; a consumer connects to four routers, which in turn connect to four content caches (the consumer can thus reach four caches over four disjoint paths). Thus, the consumer is able to exploit content multihoming, by simultaneously accessing all four

Table 1: Face selection proportions under different choices of γ.

	γ				
	0.167	0.333	0.500	0.666	0.833
LTE	$37.8 \pm 0.0\%$	$37.2 \pm 0.0\%$	$37.0 \pm 0.4\%$	$36.0 \pm 0.0\%$	$35.2 \pm 0.0\%$
WiMAX	$32.6 \pm 0.0\%$	$32.4 \pm 0.1\%$	$31.6 \pm 0.5\%$	$31.7 \pm 0.1\%$	$31.2 \pm 0.0\%$
802.11	$29.6 \pm 0.0\%$	$30.3 \pm 0.1\%$	$31.4 \pm 0.1\%$	$32.3 \pm 0.0\%$	$33.5 \pm 0.0\%$
802.15.4	$0.0 \pm 0.0\%$	$0.1 \pm 0.1\%$	$0.0 \pm 0.0\%$	$0.1 \pm 0.1\%$	$0.0 \pm 0.0\%$

caches. The consumer is connected to each router using a different wireless technology; the connections between the routers and caches are wired.

The four different RATs were: LTE (10 ms propagation delay, 150 Mbps bandwidth), WiMAX (50 ms, 70 Mbps), 802.11 (2 ms, 54 Mbps), and 802.15.4 (15 ms, 250 kbps) on each node. The links from the routers to the caches were all 10ms propagation delay and 150Mbps bandwidth. The consumer generated interests at a constant rate that saturated 90% of its outgoing link capacities; $\alpha = 0.833$, $\beta = 0.167$, $\gamma = 0.5$. The simulations run for 60 seconds and the results are averaged over 5 runs.

[Figure 4 about here.]

Figure 4 illustrates the latency and goodput achieved under each forwarding strategy. The bars LTE, WiMAX, 802.11, and 802.15.4 represent the fixed-face strategy (only one RAT chosen); Rand is the random strategy, IC-MCN is our strategy. Figure 4 (a) shows that IC-MCN achieves greater goodput than Rand, as it assigns greater weights to high-bandwidth faces by observing interest timeouts, this underscores the importance of multi-RAT. Figure 4 (b) demonstrates that weighing of faces based on latency is better than Rand. However, use of multiple interfaces results in higher averaged latency for both Rand and our strategies in comparison to the faster fixed-face configurations.

[Figure 5 about here.]

Figure 5 explores effects of variations of α, β, and γ. Figure 5(a) shows the effect of varying α ($\beta = 0.167, \gamma = 0.5$). Higher values of α give more weight to the latest latency reading, which leads to an overall reduction in latency and increase in goodput; however, the overall effect is small. In Figure 5(b), we vary β ($\alpha = 0.833, \gamma = 0.5$). Varying β has more impact on goodput than varying α; assigning a lower weight to recent measurements (smaller β) increases goodput and reduces latency. Fig. 5(c) shows the effects of varying γ ($\alpha = 0.167, \beta = 0.833$). Choosing the smallest γ optimizes both goodput and latency. However, this may just be in our scenario where queuing delay posed an adverse effect against latency optimization. Table 1 shows the proportion of interests forwarded on each interface under different values of γ. We can see that the LTE face, having the best latency and bandwidth characteristics, consistently receives the largest share of interests. Also, by increasing γ we cause the WiMAX face's shares to decrease in favor of the 802.11 face; this is consistent with the fact that 802.11 has significantly lower latency than WiMAX. Interestingly, the 802.15.4 face is still chosen to receive some interests despite its low bandwidth.

This demonstrates the effectiveness of multi-RAT statistics aware forwarding strategy, over simple randomized load-balancing,in an IC-MCN to maximize goodput while achieving lower latency. The forwarding strategy and results we have presented, represent only a preliminary evaluation of this potential, and many avenues remain to be explored. This demonstrates the effectiveness of an IC-MCN architecture.

6 Concluding Remarks

We identified the challenges from the new Internet traffic trends, driven by ever-increasing mobile traffic. We discussed the need for the design of an information-centric mobile converged network and illustrated its suitability to handle the trends. We presented our architecture and showed how it enables convergence between the Internet and the cellular core. We also presented experimental insights into leveraging of multi-RAT in the IC-MCN architecture.

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Biographies

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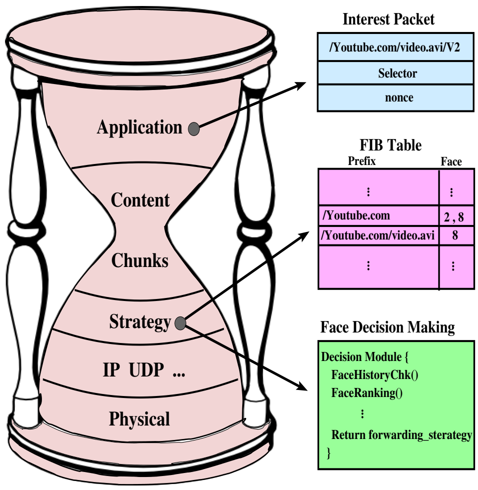


Figure 1: NDN Network Stack Model

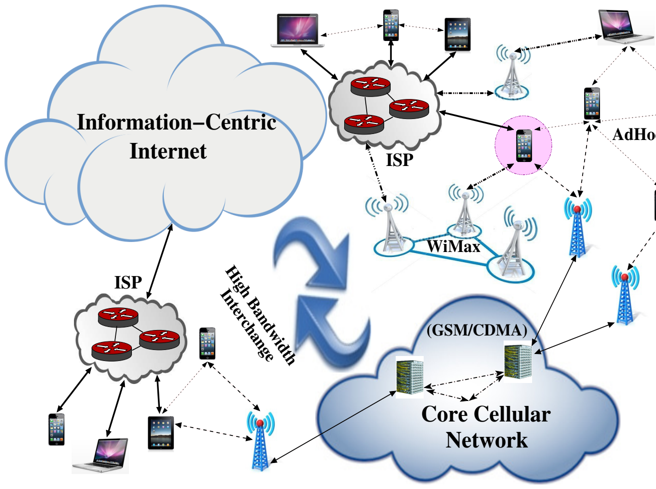


Figure 2: Information-Centric Converged Network Architecture.

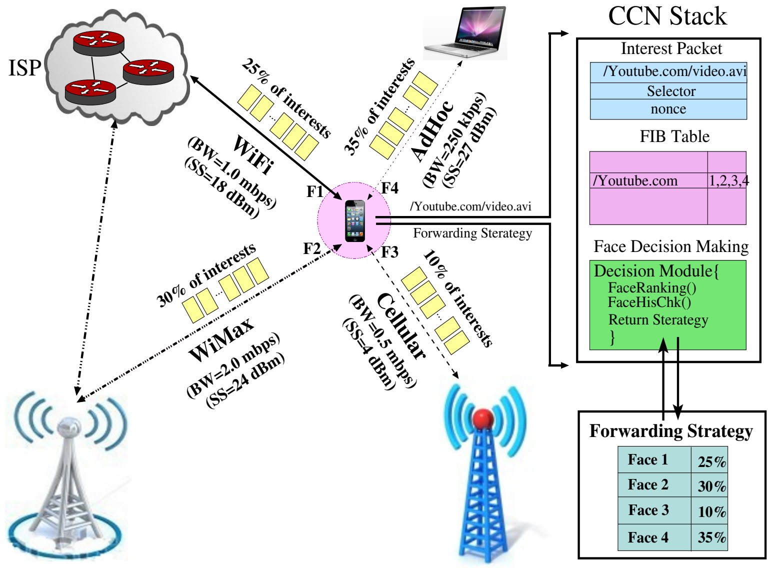
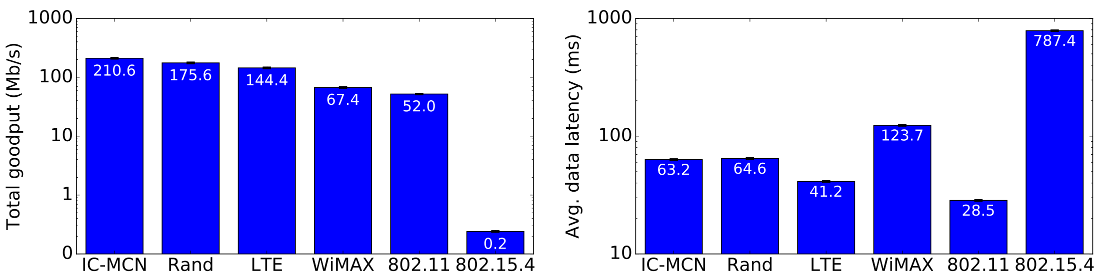
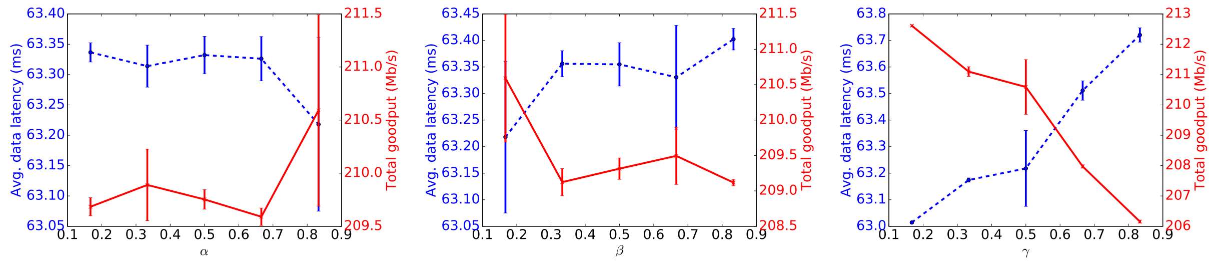


Figure 3: Leveraging the Multiple Communication Interfaces in an IC-MCN.



(a) Goodput (b) Latency

Figure 4: Achieved goodput (a) and latency (b) measurements for each forwarding strategy. We observe that weighing interfaces based on observations (IC-MCN) allows higher goodput and lower latency to be achieved than simple randomized load-balancing (Rand).



(a) α (b) β (c) γ

Figure 5: Effects of configuration parameters on latency and goodput. In each plot, we vary one parameter over $\{0.167, 0.333, 0.500, 0.666, 0.833\}$ and fix the others at their default values ($\alpha = 0.833, \beta = 0.167, \gamma = 0.500$). Latency is given by the blue, dashed line and the left y-axis; goodput is given by the red, solid line and the right y-axis.