On Content-centric Wireless Delivery Networks

Hui Liu, *Fellow, IEEE,* Zhiyong Chen, *Member, IEEE,* Xiaohua Tian, *Member, IEEE,* Xinbing Wang, *Senior Member, IEEE,* and Meixia Tao, *Senior Member, IEEE,*

Abstract

The flux of social media and the convenience of mobile connectivity has created a mobile data phenomenon that is expected to continuously overwhelm the mobile cellular networks in the foreseeable future. Despite the advent of 4G/LTE, the growth rate of wireless data has far exceeded the capacity increase of the mobile networks. A fundamentally new design paradigm is required to tackle the ever-growing wireless data challenge.

In this article, we investigate the problem of massive content delivery over wireless networks and present a systematic view on the content-centric network design and its underlying challenges. Towards this end, we first review some of the recent advancements in Information Centric Networking (ICN) which provides the basis on how media contents can be labeled, distributed, and placed across the networks. We then formulate the content delivery task into a *content rate* maximization problem over a share wireless channel, which, contrasting the conventional wisdom that attempts to increase the bit-rate of a unicast system, maximizes the content delivery capability with a fixed amount of wireless resources. This conceptually simple change enables us to exploit the "content diversity" and "network diversity" by leveraging the abundant computation sources (e.g., application-layer encoding, pushing and caching, etc.) within the existing wireless networks. A network architecture that enables wireless network crowdsourcing for content delivery is then described, followed by an exemplary campus wireless network that encompasses the above concepts.

The authors are with the Institute of Wireless Communications Technology (IWCT), Department of Electronic Engineering, Shanghai Jiao Tong University, Shanghai, 200240, P. R. China. Emails: {huiliu, zhiyongchen, xtian, xwang8, mxtao}@sjtu.edu.cn

I. Background and motivations

The growing popularity of smart mobile devices, coupled with bandwidth hogging data services and applications (e.g., Youtube), has spurred the dramatic increase in mobile traffic volumes. It is widely anticipated that the amount of mobile traffic beyond 2020 will be 1000 times higher than the 2010 traffic level [1]. This so-called "mobile data tsunami" has driven the mobile operators and wireless researchers around the world to the edge: how can the wireless infrastructures and radio communication technologies advance fast enough to keep up with this phenomenon? Various innovative capacity-increasing solutions have been proposed and investigated [2]–[4]. Among other promising techniques, i) denser base station deployment (by a factor of 10 in areas with a large density of active users), ii) additional spectra, and iii) improved spectral efficiency (by a factor of 10 through distributed antenna systems (DAS) [2], cell collaborations [4], etc.) are widely regarded as the cornerstones technologies for next generation mobile networks.

A. The myths of exponential increase in mobile traffics

While the collective solutions may indeed deliver the 1000 times capacity increase within this decade, they do not adequately address two of the fundamental issues associated with mobile traffic explosion.

- Sustainability and scalability: Given the Shannon theory bounded radio link capability, the scarcity of mobile spectra, and the environmental and operational constraints, it is unlikely that the current wireless bottleneck can be averted solely by wireless infrastructure expansions.
- Mobile traffic characteristics: Media contents constitute the lion's share of today's mobile traffic[1]. More importantly, the traffic characteristics have changed profoundly over time [5]. As such, it becomes questionable whether the unicasting optimized cellular networks are the right platform for the task of massive content delivery.

The first issue is easily appreciated since the mobile traffic growth is unlikely to stop by 2020. With diminishing returns in infrastructure-based investments, it is difficult to imagine that the next wave for mobile data tsunami can still be tackled with infrastructure and bandwidth

[1]Given the stochastic nature of wireless data, the 1000 times traffic volume increase itself does not necessarily mandate a 1000 times increase in mobile cellular capacity, defined as bits/second/Hz/m^2.

expansions. The second issue, on the other hand, offers both challenges and promises at the same time. Upon a closer examination at the wireless traffic trend, it is observed that despite of their massive numbers, the amount of "unique" media content does not actually increase exponentially [6]. In addition, even unique multimedia contents are not consumed with the same frequency, at least statistically. Studies have revealed that

- 70% of the wireless traffic is from videos [1], many with applications that personalizes the viewing experience. Specifically, users expect to be able to watch recently broadcast content and also access archived programs across different mobile platforms..
- Only a small percentage, 5-10%, of "popular" contents are consumed by the majority of the mobile users, despite the large temporal variability in the content consumption time. In particular, "personalized" viewing experience can be achieved through content pushing/caching and time-shifting [7].
- Modern media contents are increasingly decoupled from their sources. The contents of today can be modularized, labeled, separately delivered and placed across different nodes in the network, and reassembled at the user end at the time of request [5].

The above observations suggest that mobile applications are undergoing a fundamental shift, from the conventional "connection-centric" behaviors (e.g., phone calls, text messages), to a more "content-centric" usage model. The cellular networks of today, which utilize technologies such as micro- and pico-cells, frequency reuse, and directional transmissions, etc., are optimized for unicasting services so that unique information can be delivered to individual users. However, it can be argued that the logjam of the cellular networks is not due to the lack of "connection" capability (i.e., unicasting). Instead, the real problem is the ineffectiveness of the current cellular architecture in massive content delivery. In fact, it has been suggested that a converged broadcast and cellular network, akin to an integrated high-speed train and highway transportation system, might be the most efficient combination for wireless media content delivery.

B. From connection-centric to content centric

Before we dive deep into the content-centric wireless network design, a quick overview of the upper-layer advances in content creation and distribution is due first.

The inability of the mobile networks to sufficiently exploit the content characteristics is in part attributable to how contents are created and accessed in the IP-based network. Traditionally,

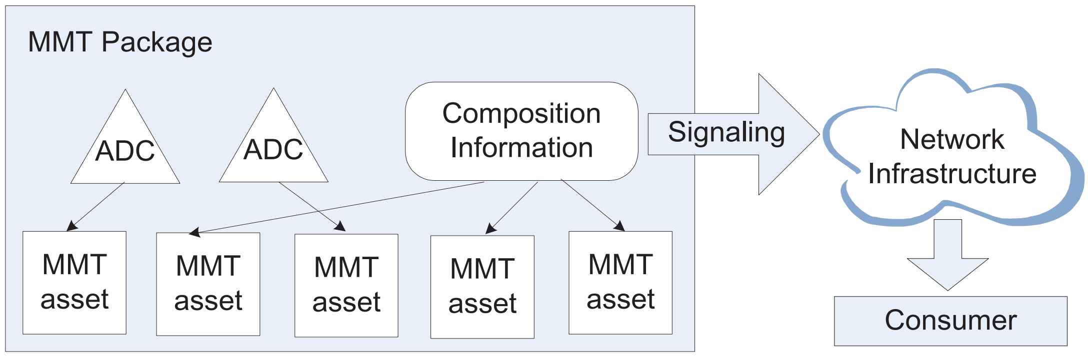

Fig. 1. MMT assets and service packages.

mobile content accessing is achieved by establishing a *link session* between the content host and the client via wired-line and wireless infrastructures. A majority of these link sessions are IP-based. The current Internet architecture was designed under the host-centric communication paradigm, which is problematic in meeting the demands of scalable multimedia applications [8] [9].

The need of fully utilizing the network resources for content distribution has motivated the development of future network architectures based on the named data objects (NDOs), which is commonly known as the information-centric networking (ICN) [8], [9]. A fundamental feature that distinguishes the ICN model from the current Internet is that the information/content is decoupled from its sources, so that a particular content can be named and placed anywhere within the network. This feature not only facilitates the information distribution, but also provides the freedom in the creation of personalized, on-demand multimedia contents. For example, a popular video could be embedded with personalized advertisement tailored to the user's preference, and patched with audio in a language suitable for users in an area. In this scenario, each of the components or the content objects, could be assigned with a name, delivered through a different path, and be combined towards the needs of different users.

The MPEG in particular is developing the MPEG Media Transport (MMT) standard in order to enable flexible content access with unique identifiable names for optimized content delivery [10]. The MMT package is a logical entity consisting of MMT Assets, Composition Information (CI), and Asset Delivery Characteristics (ADCs), which are coded media data about the content, the information about how the data should be combined and delivered, respectively - see Fig. 1. Compared with the connection-based delivery, where the service package is delivered in its entirety, the NDO content structure provides much higher flexibility and significant saving in network resources, and lands itself nicely into a content-centric wireless framework to be discussed in the ensuring sections.

In the rest of the article, we shall seek solutions to the wireless bottleneck problem by taking advantages of the newly equipped NDO features and the readily available computation resources (e.g., application-level encoding and caching) within the wireless network. The goal is to arrive at a content centric design that could potentially over multiplicatively improvement. Specifically, we shall focus on maximizing the content delivery capacity *with a fixed amount of wireless resources*. With this purpose in mind, we organize the remainder of the article is as follows.

- In Section II, we describe the new dimensions that could be exploited to achieve the set goals and provide a high level overview on the state of the art.
- In Section III, we formulate wireless content delivery into a *content rate* maximization problem over a shared wireless channel. This change of design paradigm enables us to quantify the *content diversity* in wireless delivery. A priority encoding transmission (PET) [11] based joint transmission scheme is then described, which reveals important insights regarding how computations (encoding and caching) can affect the wireless content delivery capability.
- In Section IV, we focus on the *network diversity* and generalize the framework to multiple wireless networks where the notion of "network crowdsourcing" for content delivery is established. A network architecture that enables wireless network crowdsourcing is then described.
- Finally in Section V, we illustrate the feasibility of content-centric wireless networks with an exemplary campus wireless network that encompasses the above concepts.

II. Exploiting new dimensions in wireless content delivery

Historically, leapfrogs in mobile communications are often associated with the discovery of new dimensions and diversities. The breakthroughs in time-frequency, code, space, and multiuser diversities have been the sources of cellular bit rate breakthroughs (by three orders of magnitude) for the past three decades. In light of the fact that the mobile media contents are highly diversified, both in characteristics and distribution channels, we can anticipate a dramatic increase of the ability of mobile content delivery by exploiting the so-called "content diversity" (at application level) and "network diversity" (at infrastructure level), via approaches that take advantage of the computation and caching capabilities within the wireless networks.

Various approaches have been attempted to exploit the content and wireless network diversities. In particular, the so-called *converged network*, which combines broadcasting with cellular, provides a highly efficient and practical means to simultaneously capture the content and network diversity gains. A number of results have been reported on converged network. The authors in [12] proposed and analyzed a hybrid scheduling scheme for mixed multicast and unicast traffics in cellular systems. A collaborative scheme is proposed in [13] to optimize the trade-off between the amount of parity data transmitted by the broadcasting station and repair data delivered through cellular channels to users with missing information from broadcasting. For the purpose of reducing the delivery cost, the authors in [14] adopt application layer forward error correction with Raptor coding to repair errors of the initial DVB-H broadcast using HSDPA and MBMS channels. In [15], mobile-TV services are delivered through hybrid broadcast-unicast, and it is pointed out that only programs with high viewing probability should be delivered over broadcast. Exploiting the user behaviors, [16] proposed an energy efficient multicast scheme with patching stream which enables the transmitter to deliver both patching stream through unicast transmission and shared stream through multicast transmission. The converged information delivery was considered in 3GPP and 3GPP2 back in 2002, when both organizations created items for broadcast/multicast services in GSM/WCDMA and CDMA2000, respectively. Broadcast services delivered in 3G networks is introduced in [17], in which the authors argue that the hybrid unicast-broadcast delivery is superior not only in terms of the system resource usage but the user experience. In [18], [19], more application scenarios on broadcast services in 3G networks and beyond are described. Most recently, $AT\&T$ announced its plan [20] to use 700Mhz channels for LTE Broadcast networks to remove video from its wireless network, clearing those airwaves up for other data.

At the algorithmic level, the content diversity gains are achieved by taking advantage of the abundance of computation power (e.g., application layer encoding and decoding) and caching capacities within the wireless networks. The major benefits of content caching in wireless applications include i) minimizing the content downloading time, ii) alleviating the traffic loads on the core networks, and iii) mitigating the over-the-air wireless traffics. Niesen et al investigated the inner- and outer- bounds on the caching capacity region for a generic wireless network with n nodes [21]. Most practical caching schemes assume a *two-phase caching strategy* which involves a placement phase and a delivery phase [22]. By delivering the popular contents, either in their entirety or in pieces, to nearby stations (e.g., basestations, relay nodes, helper nodes, etc.) during the placement phase, the user *downloading delay time* can be minimized [23], [24]. These approaches however, do not actually reduce the wireless traffics within the networks.

For the purpose of reducing the over-the-air wireless traffics, it has been proposed that the contents can be placed to user devices during the wireless off-peak time, so that the wireless network peak rate can be greatly reduced [22]. A novel architecture with distributed caching of video contents in femto-base stations and wireless terminals is described in [6]. Several network coding-based content placement approaches have been proposed and analyzed [25] [22]. All these approaches assume a high level of *temporal variability* in wireless network traffic. Nevertheless, they do not reduce the total amount of the over-the-air traffic loads. To date, only limited research attempts to combine the content diversity with caching/encoding in order to reduce the *total amount of wireless traffics*.

III. CONTENT-CENTRIC WIRELESS DELIVERY

Despite the various schemes that exploit the content characteristics in wireless delivery, the *content diversity* has not been quantified under a unified framework, even under the simplest multiuser scenario. In this section, we introduce a novel information-theoretical formulation for the content delivery problem. In particular, the notion of wireless *content rate* is established, which, in contrast to the *bit rate* of a wireless unicast system, characterizes a direct relation between the content diversity and the content delivery capability of a wireless system.

A. Content rate formulation

The capacity of a wireless system is traditionally measured by the bit rate at which unique information is reliably transmitted over the wireless system. In order to quantify the effectiveness of wireless content delivery, we must first distinguish the bit-rate with the so-called *content rate*, defined in the ensuring section. We will show that for a wireless system with *fixed bit-rate*,

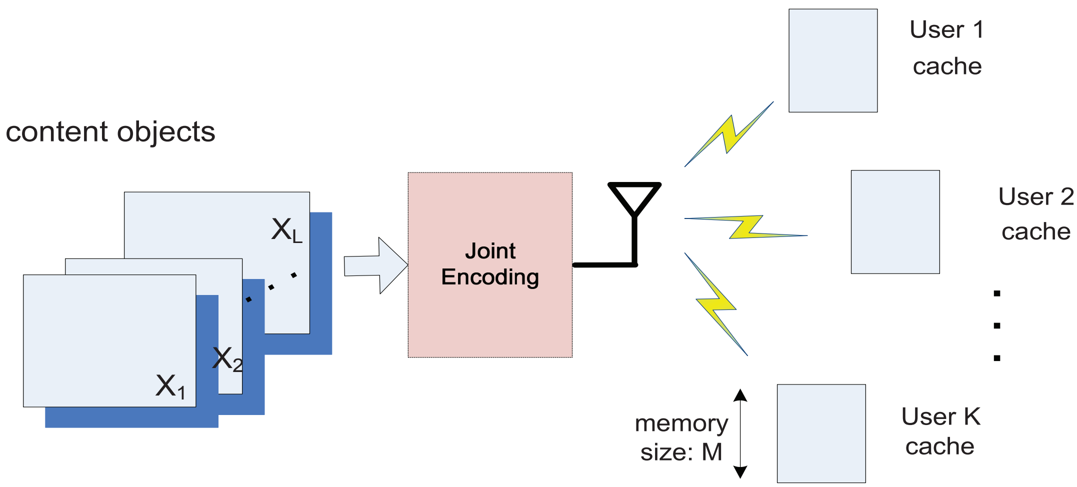

Fig. 2. A scenario where L content objects are available for delivery to K users in the wireless system.

its content rate could be increased substantially, depending on the content diversity and the computation power within the wireless system.

To elaborate, consider the scenario in Fig. 2 where L content *objects* (e.g., MMT assets) are available for delivery to K users in the wireless system. The set of independent content objects is denoted as $\{x_l\}$, each with the size $|x_l|$ bits, $l = 1, \cdots, L$. To receive personalized services, each user would request a particular service package at a specific time. We denote such a request from the k-th user at time t_k as $y_k(t_k)$. Unlike a conventional wireless system which delivers y_k in its entirety through unicasting, portions of the content objects will be sent and cached at the user end before the actual request. To understand the above process, let

$$y_k(t_k) = \{f_k(x_{k_1}, x_{k_2}, \cdots, x_{k_i}), t_k\}, \tag{1}$$

where $(x_{k_1}, x_{k_2}, \cdots, x_{k_i})$ are the set of content objects needed for request y_k, and f_k is the content representation function, i.e., how content modules are processed and represented to the user. For simplicity, we shall assume $f_k = \bigcup\{x_{k_1}, x_{k_2}, \cdots, x_{k_i}\}$, i.e., the union of all the content objects needed by k-th user in the remainder of this paper.

Clearly, as long as the corresponding content objects are received by the user before t_k, the k-th user's request can be satisfied. Accordingly, we can define the wireless content rate as *the rate at which the amount of service packages $\{y_k(t_k)\}$ successfully delivered to users through the shared wireless channel.* Such a measure is more suitable for the problem of interest since, for content delivery purpose, the users are only concerned with the amount of service packages received while the wireless carriers are mostly keen on the number of satisfied users on the network. To formulate the content rate mathematically, assume a *shared* wireless channel with fixed link rate $= 1$b/s/Hz. Further denote

- B: the bandwidth of the wireless channel
- M: the maximum user cache length
- $\mathbf{Z}$: the content diversity matrix ($K \times L$) that maps content objects to users. Each element of the matrix is either 1 or 0. If $Z_{kl} = 1$, it means the k-th user is interested in the l-th content module; otherwise it is not.

***Definition** 1:* Given a fixed amount of wireless resource $B \times T$ ($T = \max\{t_l\}$), the *content rate* R_C is defined as the total amount of service packages successfully delivered to the users:

$$R_C = \frac{\sum_{k=1}^{K} |y_k(t_k)|}{B \times T}. \tag{2}$$

***Definition** 2:* $\{R_C, M, \mathbf{Z}\}$ is *achievable* if there exists a transmission strategy for a given wireless resource $B \times T$ such that all users are able to successfully receive their requested service packages before their respective requesting time instants.

Since R_C is inverse proportional to the bandwidth B, the content rate is maximized when all users requests are met with the minimum amount of bandwidth: $\min B \Longrightarrow \max R_C$.

B. The content rate bounds

Determining the achievable $\{R_C, M, \mathbf{Z}\}$ is non-trivial to say the least. First of all, the content objects $\{x_l\}$ are neither *private* nor *common*, and therefore, they cannot be efficiently delivered with a unicasting or a broadcasting mechanism alone. The content delivery ability of the wireless system depends on several factors:

1) how the content objects are mapped to the user requests (i.e., $\mathbf{Z}$);
2) how content objects are jointly encoded and delivered over the shared wireless channel;
3) the amount of caching available at the user ends, so that content objects can be delivered before the service requests.

Interestingly, the later two factors are determined by the *computing capability*, i.e., application-layer encoding/decoding and caching, rather than the communication capability of the wireless

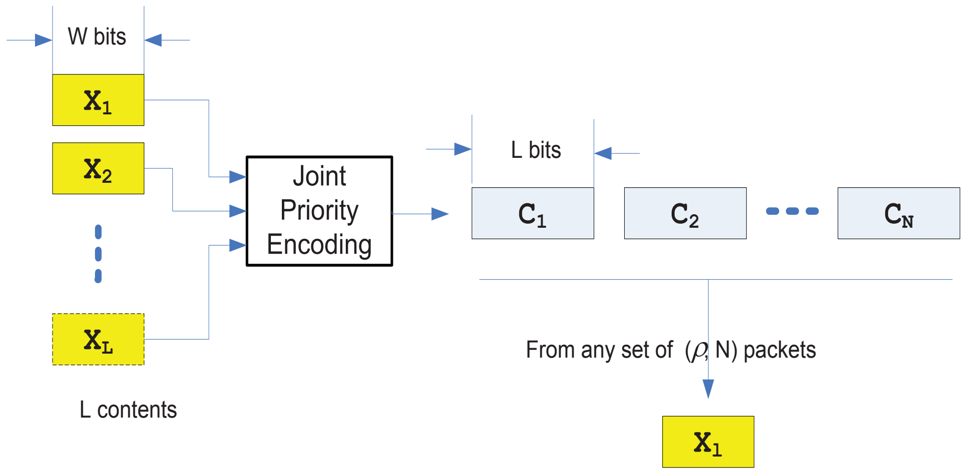

Fig. 3. Priority encoding for content diversity.

system. As such, optimizing the content rate must be conducted under a *computing-communication* framework, which simultaneously exploits the communication and computation limits of the wireless system.

The following lemmas shed some light on how the content rate relates to the wireless system bit rate.

Lemma 1: The content rate *upper bound* of a shared wireless channel is reached when $\{t_i\} = T$, $M = \infty$ (i.e., infinite caching), and all content objects being broadcast and cached at the user ends. In this case, the minimum amount of bandwidth required is given by $B_{\text{min}} = \sum_{l=1}^{L} |x_l|/T$.

Lemma 2: The content rate *lower bound* of a shared wireless channel is reached when $M = 0$ (i.e., zero caching), and each content object being unicasted to individual users at different requesting times. In this case, the maximum amount of bandwidth required is given by $B_{\text{max}} = \sum_{k=1}^{K} |y_k|/T$, and the content rate reduces to $R_c = 1$b/s/Hz, the wireless system bit-rate.

In other words, broadcasting with unlimited caching at the user ends delivers the highest content rate, whereas unicasting upon individual service request is the least efficient way of using the wireless resources in content delivery.

C. Priority encoding for content diversity

In practice, approaches such as application-layer encoding with user-end caching can be employed to increase the content rate R_c. An elegant scheme, termed the *priority encoding* *transmission* (PET), was introduced by Albanese et at in 1996 [11] to capture the content diversity with joint source encoding.

Consider the scenario depicted in Fig. 3, where the content objects $\{X_l\}$ are to be delivered to the users with caching capability. Instead of sending the objects individually, the content objects can be jointly encoded to save the wireless bandwidth. At the same time, since the content objects are not requested at the same frequency, the content priorities must be accounted for at the encoding stage to benefit the decoding. Applying the PET principle to wireless content delivery, $\{X_l\}$ are jointly encoded with *priority* based on their degree-of-interests.

***Proposition** 1:* Let $\rho_l \subset (0, 1], l = 1, ..., L$, be the priority index of *the lth content object. There exists a priority encoded sequence consists of (Albanese et al [11]): An encoding function that maps the content set $\{X_l\}$ onto an encoded sequence of N packets, with Γ bits each, and a decoding function that maps the N packets onto the L contents. The decoding function is able to decode the lth content from any ρ_l fraction of the N encoding packets.*

By making $\{\rho_l\}$ inverse proportional to the content popularity, content objects with higher priorities will be decodable from fewer coded packets, whereas objects with lower priorities are decodable from more packets. Applying the PET scheme to jointly content object encoding as shown in Fig. 3, the content rate is increased while the average caching size is also minimized accordingly.

IV. Wireless network crowd-sourcing

Given that the modern contents can be distributed and placed across the networks, and the fact that wireless users often have access to various forms of wireless channels (i.e., network diversity), we examine in this section the feasibility of wireless content delivery over multiple wireless infrastructures, potentially from different wireless network service providers (NSPs).

The current wireless NSPs face multifaceted challenges. On one hand, the amount of traffics delivered over their wireless networks will continue to grow exponentially in the foreseeable future. On the other hand, the profits made from traditional pipe-like services are not increasing in line with the traffic increase rate. Particularly, the super active over-the-top (OTT) service providers (e.g., Google, Amazon, Netflix, etc) are revolutionizing the way people are using the network, and at the same time, undercutting the traditional business model of the NSPs. The most representative OTT service is the high-quality multimedia distribution, which is and will

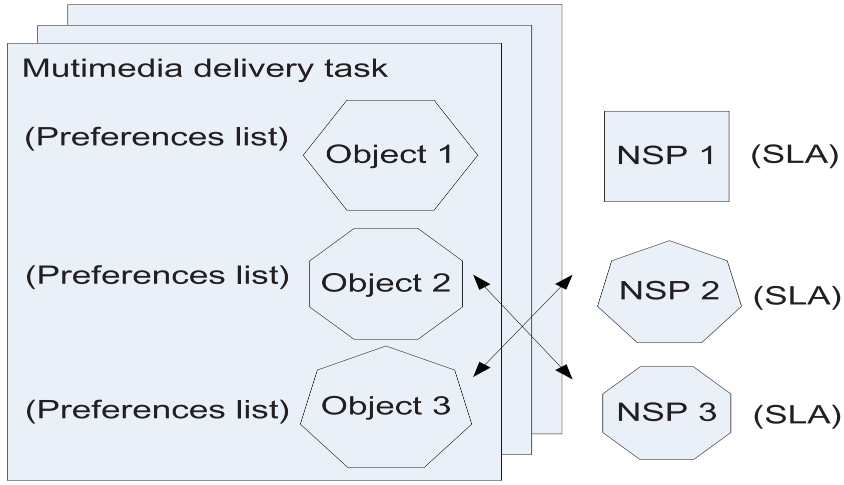

Fig. 4. Network crowdsourcing for wireless content distribution.

be the dominant wireless traffics. The accelerating trend is motivating NSPs to seek innovative service models and partnership in responsive to the new economy driven by the OTT innovation.

We propose a collaborative model between the OTT Content Provider (OCP) and wireless NSPs termed as *Network Crowdsourcing*, which is illustrated in Fig. 4. The NSPs are acting as contractors to undertake the task generated by the OCP, where each task should be the delivery of modularized content objects. Each NSP provides the OCP a service level agreement (SLA) showing how certain object could be delivered. The SLA should specify at least the following information: i) the network resources to be allocated to the object distribution, ii) the expense the OCP should spend for the object distribution, and, iii) the management functionalities can be provided to the OCP. Based on the SLAs offered by NSPs, the OCP may choose a group of NSPs to accomplish the content distribution task, therefore the notion of "network crowdsourcing". The OCP can also provide task profiles specifying the preferences of each objects distribution subtask, including the amount of resource needed, budget and preferred management interfaces.

Under the network crowdsourcing model, the OCP and clients could communicate with each other on which kind of network resources the client is able to utilize. For example, the client user may see multiple wireless networks owned by different NSPs, and each NSP may provide different kinds of access schemes such as broadcasting, WiFi and cellular. By aggregating such information, the OCP could understand the popularity of each object and the geographic distribution of clients served by each NSP, which could in turn greatly help the OCP generate the task profile.

From the perspective of the NSP, the current trend towards software defined networking (SDN) [26] technology provides the unique opportunity for the NSP to obtain more effective control and scheduling of its network resources. In particular, the SDN decouples the control plane and data plane of networking routers and switches, which enables the global control and management of the network fabric. The SDN controller can facilitate checking whether the required network resources are available; moreover, it can provide interfaces for applications to realize certain control and management functionalities.

A. Network Architecture and delivery schemes

Under the above framework, we now describe a network architecture that enables network crowdsourcing in massive content delivery, as shown in Fig. 5. Specifically with this architecture, the OCP can negotiate with the NSPs for distributing contents, based on the task preference and SLA provided by NSPs. Through interactions, the ~~OSP~~ develops an understanding of the content demand distribution and the particular users' contexts through its communication with users. Each NSP maintains effective control over its networking resources, with the facilitation of SDN or similar technology. The negotiation protocol can work on the application layer interfacing the OCP and NSP's network management application over the controller. After the negotiation process, the network distributes the modularized objects over the ICN. According to the popularity of each object and the location distribution of users, the objects will be pushed to and cached at corresponding parts of ICN, in order to facilitate wireless delivery through access networks. Users will obtain the requested content through channels based on different access techniques, and even from different NSPs. The objects can then be reassembled to form a playable content.

V. AN EXEMPLARY CONVERGED NETWORK

In this section, we present an exemplary wireless campus network where the content diversity and the network diversity is exploited within a broadcast-cellular-WiFi converged network.

Lemma 1 in Section III-B suggests that with sufficient caching capability at the user ends, broadcasting may be the most efficient means to deliver massive contents to wireless users. In

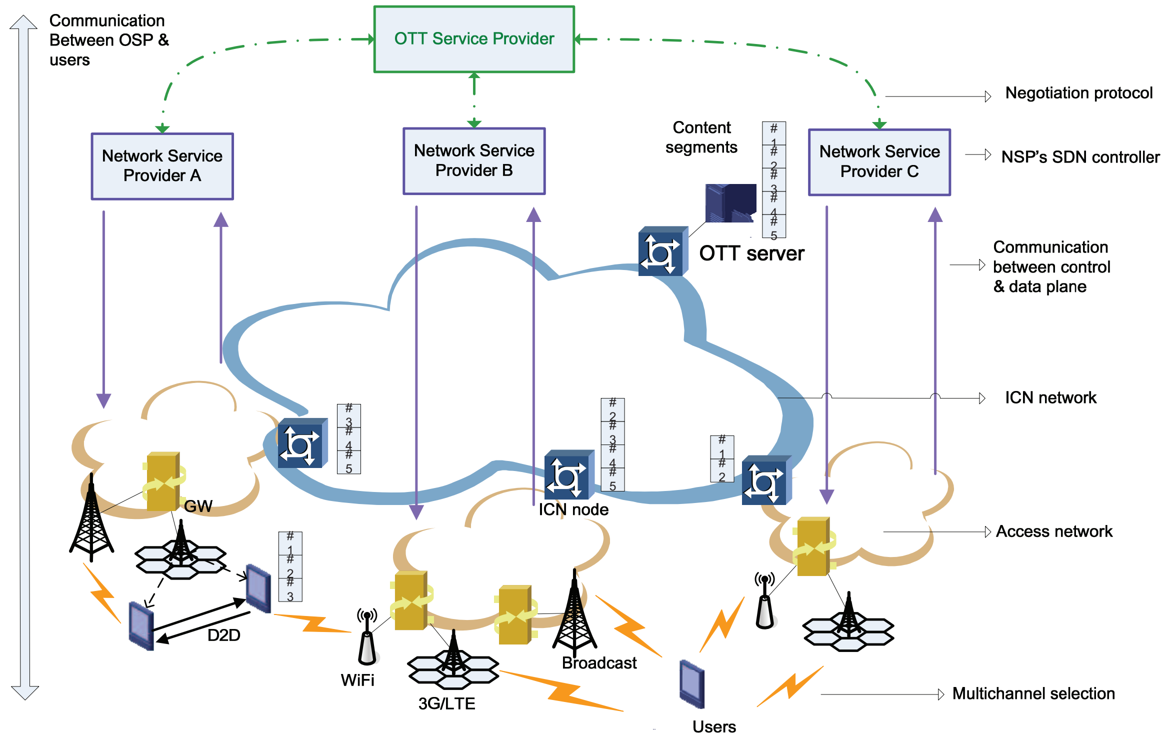

Fig. 5. A network architecture that enables network crowdsourcing in massive content delivery.

practice however, the memory size at a mobile device is always limited. In addition, the long tail of the Zipf distribution cannot all be accommodated with broadcasting. A broadcast-cellular converged network provides a more sensible solution to the wireless content delivery [12], [13], [27], [28].

A. The large-scale campus wireless network

In collaboration with Huawei, a large-scale wireless test network has been established on the 3 square kilometer campus of Shanghai Jiao Tong University (SJTU). The deployment is scenario depicted in Fig. 6. The heterogenous wireless network is comprised of an LTE cellular system, a CMMB based digital broadcasting system, and a WiFi system. In particular, the campus network features

- 80+ micro- and pico- stations, providing blanket coverage of the entire campus
- over 66 kilometers of fiber, connecting all cellular RF transceivers to form a truly cloud-based radio access network (C-RAN)
- 3 single-frequency-network (SFN) digital broadcasting stations

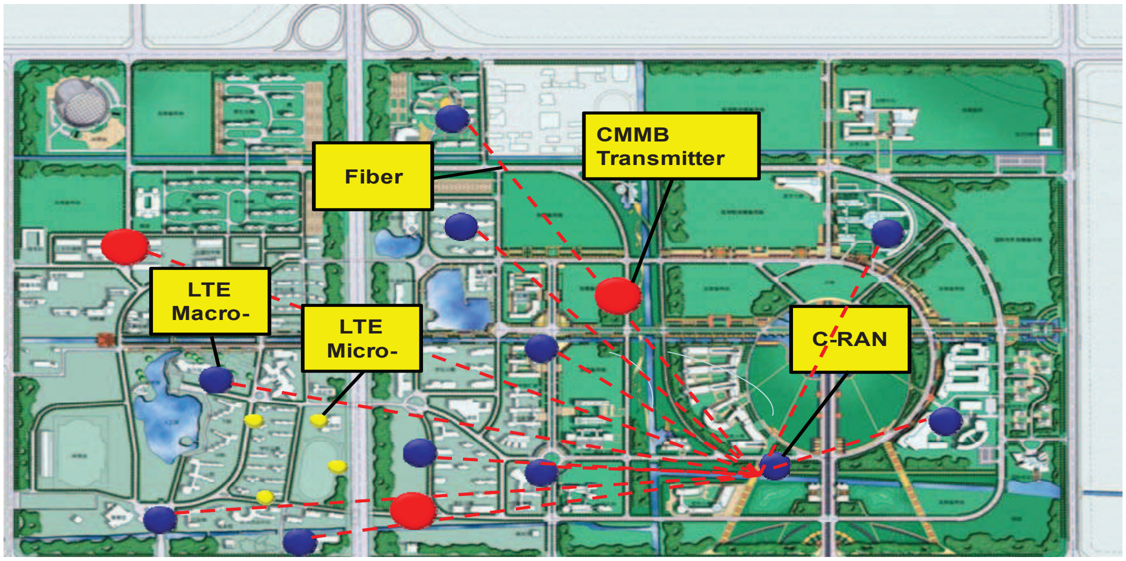

Fig. 6. A large-scale wireless campus network in Shanghai Jiao Tong University

- 2500+ WiFi APs across the campus

The broadcasting system, the cellular system, and the WiFi system work collaboratively provide a high-speed data and media delivery services to trial mobile users/clients that include students and faculty, campus shuttles, wireless surveillance cameras, EVs, etc. The users under the coverage of the converged network can receive services from both the broadcasting system and the cellular/WiFi system.

Specifically for the content delivery applications, the three wireless systems are *converged to form a push-based service platform,* so that the multimedia contents can be delivered to the users via: i) broadcasting with pushing and caching, and/or ii) unicast delivery through cellular/WiFi networks. A *content scheduler* is utilized to update the pushing list which is comprised of the most popular contents [28]. The analysis in [28] shows that the push-based converged network can bring potentially *multifold* benefits in terms of content delivery capacity and user experiences (e.g., downloading time, etc).

Currently, technical trials that involves about 500 users are underway on the campus converged network. The goal is to implement selective algorithms and schemes, e.g., the PET scheme and the network crowdsourcing scheme described in this article, so that they can be validated and optimized for real world applications.

VI. CONCLUDING REMARKS

In this article, we have exploited and motivated a content-centric design framework for massive wireless content delivery. The centerpieces of our discussions are the application-level *content diversity* and the infrastructure-level *network diversity*, which we assert can be effectively captured by taking advantages of the computation resources within the wireless networks. For the content diversity specifically, we have formulated the so-called *content rate* to provide a precise measure on the content delivery efficacy of a wireless system. A corresponding joint encoding scheme based on the PET algorithm has been presented. On the network diversity side, we have introduced the notion of *network crowdsourcing* and its supporting architecture to enable content delivery across different wireless platforms. As part of the ongoing and future work, we are implementing and evaluating selective design concepts on a large-scale wireless test network on the SJTU campus. We anticipate the outputs to provide validations and critical insights on the design of content-centric wireless delivery networks.

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