CHORUS: A Framework for Scalable Collaboration in Heterogeneous Networks with Cognitive Synergy

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Abstract

We propose a unified framework called Collaborative Harmonized Open Radio Ubiquitous System (CHORUS) that can jointly optimize heterogeneous wireless networks. To support large-scale collaboration, cognitive synergy is exploited to collect the status of multiple radios and layers, namely the network state information (NSI). Based on cognition results, resource virtualization and harmonious collaboration control are applied to optimize the global performance. We present the architecture, design challenges, and key technologies of CHORUS through our initial research efforts. We illustrate how to use cognition to interact with collaboration among multiple base stations (BSs), between BSs and relays, and among heterogeneous networks so as to save the network energy consumption. We also provide examples of cognition design across communication and broadcast networks based on traffic load and service contents information.

Introduction

To overcome the scarcity of wireless spectrum and meet the ever-growing user demand, convergence of multiple heterogeneous networks with node collaboration has been regarded as a promising and practical way to efficiently utilize wireless resources, compared with the expensive "clean slate" redesign of a one-fit-all wireless system.

Collaborative communication is firstly proposed for relays [1] with enhanced transmission diversity. It is then extended to multiple base station (Multi-BS) collaboration [2] for combatting inter-cell interference. These research efforts have triggered the standardization of collaboration techniques, such as relaying and coordinated multi-point (CoMP) in 3GPP [3].

Moreover, collaboration is exploited for seamless inter-working of heterogeneous radio access networks. For instance, network selection can be triggered by user terminals through vertical handover, and controlled by network-side admission control [4]. People also consider implementing new types of BSs with different coverage capabilities, e.g., femtocell and picocell, to bring heterogeneity into a single radio network [5], and this improves coverage, interference suppression, and resource allocation flexibility.

However, existing collaborative communication solutions, either intra-system or inter-system, are only applicable to limited scale [6], or they merely provide access flexibility among heterogeneous networks without being able to support ubiquitous access for users. For heterogeneous network convergence, it is ultimately desired to choose the best radio network for any service or even each packet so that the system resource is efficiently managed in a finer granularity. However, achieving this goal faces following challenges. First, collecting a large amount of system information from network entities and heterogenous networks is difficult, due to not only the huge mass, but also different system architectures. Second, it is hard to find the collaboration opportunities, which is also tightly related to how the supporting information is collected. Last but not least, since different radio networks are independently designed, their resources, such as power, frequency, time and space, may have different forms so that their control interfaces also vary.

To address above challenges, we introduce *cognitive synergy* that incorporates interaction between cognition and collaboration. Originally proposed for cognitive radio [7], smart cognition has been used to sense the spectrum usage and channel state information (CSI), in order to assist opportunistic transmission for unlicensed users [8]. We *broaden* the cognition targets from spectrum and CSI to network state information (NSI) of multiple layers across heterogeneous networks. To reduce the information collection and process overhead, *distributed* cognition of NSI is supported by node collaboration. Moreover, *self-organization* of network configuration

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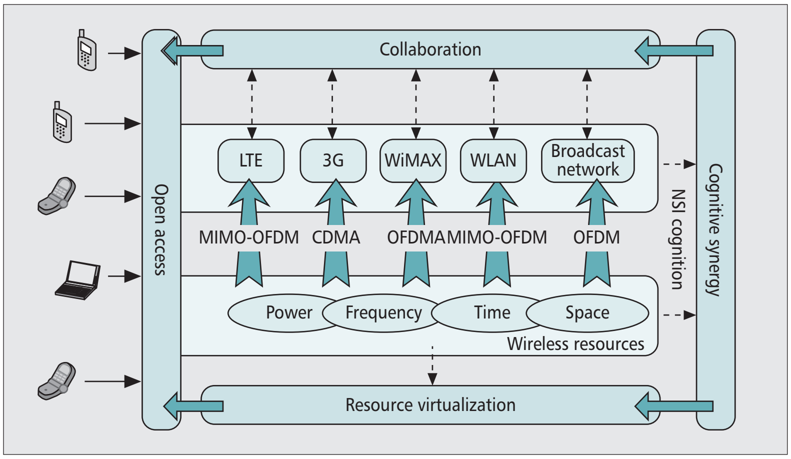

Figure 1. *The concept of a ubiquitous radio network.*

and collaboration are performed based on cognition results. Cognitive synergy is also able to provide unified *virtualization* of the resources from heterogeneous networks, which is important for traffic offloading and open access over heterogeneous networks.

Our basic vision on the new paradigm of a ubiquitous radio network, as depicted in Fig. 1, is explicitly embodied with a framework design namely Collaborative Harmonized Open Radio Ubiquitous System (CHORUS). The goal is to achieve the harmonious utilization of wireless resources and environmental friendliness by cognitive synergy in ubiquitous radio network environments. The rest of the article includes the architecture of CHORUS, its workflow, features and research issues. Then we illustrate the way of exploiting synergetic cognition in CHORUS through our initial research work.

Architecture and Features of CHORUS

Architecture and Workflow of CHORUS

The architecture of CHORUS framework is designed to work with all available wireless access networks, such as LTE/LTE-A, 3G, WiMAX, WLAN, broadcast network, etc., as presented in Fig. 2. This enables CHORUS to provide open access and unified services to any terminal. The CHORUS server, which controls the procedure of CHORUS, can be either implemented in the gateway, such as radio network controller (RNC), with centralized algorithms, or distributed in the BSs with decentralized schemes. The CHORUS server has two engines. One is the *cognitive engine*, consisting of *data analyzer* and *cognition controller*. The data analyzer communicates with the entities in the network to collect NSI, and analyzes the information to provide virtualization of the wireless resources. The cognition results are stored in the other engine: *profile database*. In following steps, the profile database can deliver back the historical cognition results to the cognition controller for node collaboration and resource reconfiguration. The delivered contents also include how the network should sense the NSI more efficiently. As shown in Fig. 2, the workflow of synergetic cognition includes four major steps: *Detection*, *Analysis*, *Decision*, and *Reconfiguration*:

- Detection is performed by access network entities to get necessary information for corresponding cognition. Same as the way that CHORUS server is implemented, the detection can be accomplished by a central controller with feedback from network elements, or with decentralized mechanisms assisted by node collaboration.
- With sufficient information, data Analysis is executed by the data analyzer based on the detected NSI and historical information in the profile database. Certain techniques, such as data mining and learning algorithms are used to virtualize the network resources. The data analyzer also in turn updates the profile database with the new cognition results.
- Afterward, the network Control and Reconfiguration decisions are made by the cognition controller and sent to user terminals and networks, and thus on-demand collaboration is harmonized with the network state. The cognition controller also refines the knowledge of the most valuable NSI for Detection. This closed-loop for detection and cognition is also important for scalable NSI collection.

Features of CHORUS and Research Issues

Exploiting NSI Rather than CSI — To realize scalable collaboration across heterogeneous networks, the NSI, as the cognition target in CHORUS, includes not only CSI, but also traffic load, service contents, user locations, access point (AP) or BS locations, spectrum resource occupancy, etc. Designing NSI-aware node collaboration and resource management mechanisms is a valuable research issue under the CHORUS framework. In the next section, we will illustrate how to use traffic load information for BS sleeping control, and how to use service contents to save transmission cost with smart caching.

Resource Virtualization — The duty of resource virtualization in CHORUS is to establish a unified and quantitative mapping between the service requirement and the wireless resource occupancy of heterogeneous networks, which is the key to the *open access* of wireless spectrum. The main research challenge lays in the different protocols and architectures of the independently designed networks, and one needs to generalize the concept of software-defined radio to the network scale [9]. Later in this article, our previous work on resource virtualization of broadcast and communication networks for the convergence of these two is introduced.

Interaction between Cognition and Collaboration — To collect NSI efficiently, network entities collaborate with each other, after which the cognition results help reconfigure the scale and the way of collaboration. In many cases, it is not feasible or not efficient to have centralized control of the network, especially in heterogeneous network scenarios. With node collaboration, CHORUS allows decentralized NSI collection and resource virtualization, and thus provides feasibility for

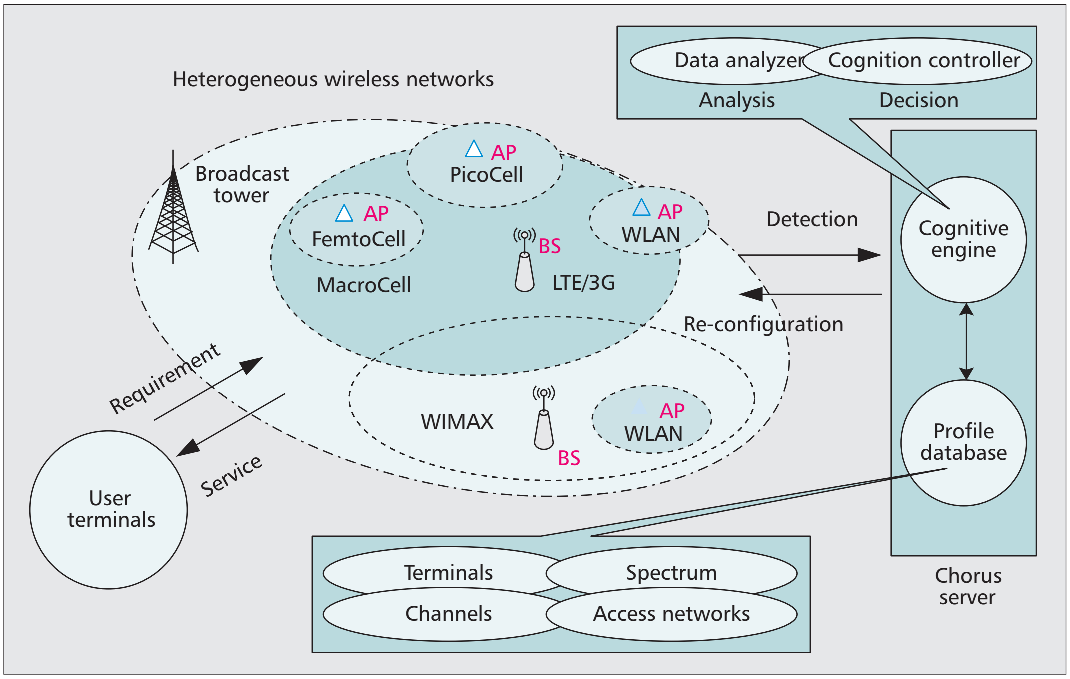

Figure 2. *The architecture of the CHORUS framework.*

Dynamic clustering itself is challenging as cluster formation relies on user scheduling, precision and scale of available CSI, user distribution, etc., which in turn incur extra overhead. In our work, CHORUS reduces these overheads and provides suitable BS clustering formation structures.

self-configuration and *autonomous organization* among transmission nodes. For example, as shown later, *distributed negotiation* for dynamic collaboration is a scalable way of transferring NSI and making joint control decisions, and thus the overhead of NSI collection and exchange is reduced. Research issues also include a self-adaptation scheme for interworking of heterogeneous networks based on the resource virtualization.

Cognitive Synergy in CHORUS: Case Studies

In this section, we show the benefits of exploiting cognitive synergy in CHORUS through two studies that realize *Scalable Collaboration* and *Ubiquitous Access*, correspondingly.

Scalable Collaboration

With cognitive synergy, the network can have harmonious collaboration with reduced NSI collection overhead, and the form and scale of collaboration are self-adapted. The first one is reflected in the Detection and Analysis steps, while the second is enabled through the Decision and Reconfiguration steps. We illustrate how these two capabilities are realized with our research on distributed dynamic BS clustering [10] and dynamic BS sleeping [13] for cellular systems.

Implementing collaborative communication is in fact a trade-off between performance gain and resource consumption on information sharing. Taking BS collaboration for example, signals from multiple cells are used to assist transmission instead of acting as interference, and thus substantial increase of the spectrum efficiency can be achieved [10]. However, due to practical constraints like CSI feedback, synchronization, and backhauling, only a limited number of BSs are allowed to collaborate [10], where the collaborating BSs form a BS *cluster*. Accordingly the whole network is divided into disjointing clusters. However users at cluster edge still suffer from severe inter-cluster interference, and thus adaptively tuning the BS cluster is more effective. In fact, dynamic clustering itself is challenging as cluster formation relies on user scheduling, precision and scale of available CSI, user distribution, etc., which in turn incur extra overhead. In our work, CHORUS reduces these overheads and provides suitable BS clustering formation structures.

The architecture of BS collaboration under the CHORUS framwork is shown as Fig. 3, where BSs are separated into three different clusters. The conceptual elements in Fig. 3 have the following realizations. The cognitive engine is implemented in each BS, and for the Detection step it abstracts the NSI (here NSI refers to CSI and QoS requirements) of clustering companions of each BS b into a preference function $\hat{R}(b, c)$, which represents the expected rate of the associated users if b joins cluster c. Then the virtualization of the resource utilization efficiency of a cluster c, denoted by $V(c)$, is defined as the sum of $\hat{R}(b, c)$ from each component BS. The exchange of above information is achieved in the form of distributed BS negotiation to accomplish low complexity BS clustering. The detailed algorithm can be found in [10]. The sum rate performance is shown in Fig. 3. It is observed that BS collaboration enjoys significant throughput gain over single BS transmission, and dynamic clustering scheme outperforms static clustering substantially. Moreover, from Fig. 3 one can see that both the feedback and calculation overhead scale slowly with the network size: The feedback overhead is almost irrelevant to the network size when the network size is large

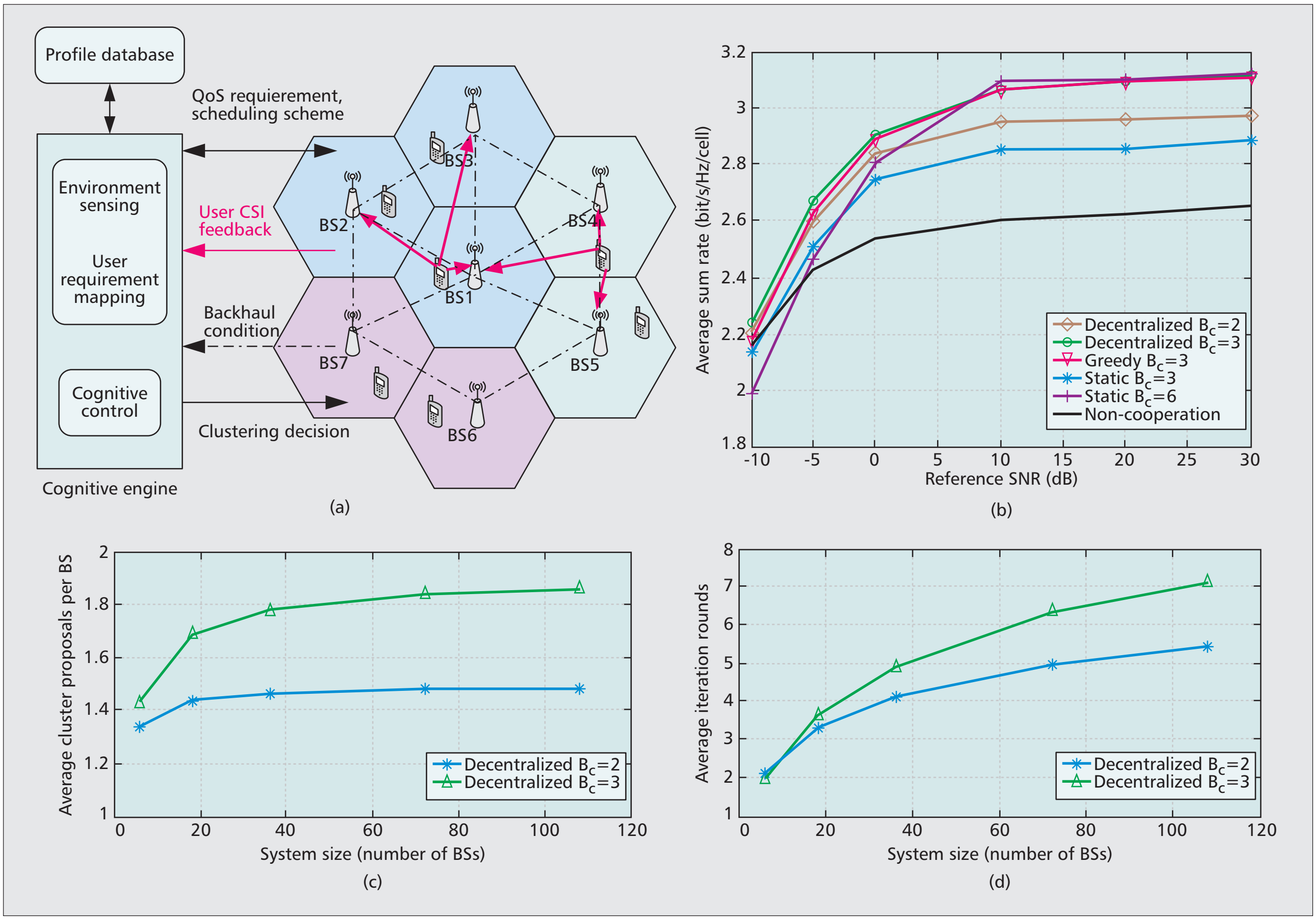

Figure 3. *CHORUS application for BS collaboration, where* B_c *is the cluster size: a) architecture of dynamic BS clustering under the CHORUS framework; b) average sum rate with dynamic BS clustering; c) feedback overhead; and d) calculation complexity. Simulation figures from [10].*

enough, and the calculation overhead scales approximately logarithmically with the network size, while the complexity of conventional centralized greedy algorithm scales quadratically with the network size.

Furthermore, with cognitive synergy, scalable CSI feedback optimization is considered in [11], where we design dynamic clustering with the consideration of limited feedback bits. We propose a feedback set adaptation scheme by the cognition of most valuable BS CSI feedback bits. The scheme successfully achieves a good tradeoff between collaboration gain and CSI quantization precision, and it further reduces collaboration overhead.

BS collaboration can also be used to save energy. Reducing the energy consumption has become one of the key features of future network design. It has been shown that BSs cost most of the energy of the access network [12], therefore switching on and off BSs *on demand* can be efficient. In accordance with BS sleeping, cell sizes of active BSs should also be tuned to guarantee the network coverage, namely cell zooming [12]. Both of above highly rely on the precise cognition of the network temporal-spatial traffic conditions. BS sleeping requires BS collaboration so that users in sleeping cells are taken care of by the active BSs. On the other hand, taking signaling overhead, device lifetime and switching energy consumption into account, frequent BS mode switching should be avoided.

In CHORUS, we use traffic cognition to assist BS sleep control. As shown in Fig. 4, the functions are implemented in the cell zooming server. For cognition operation, here the neighboring BSs negotiate to exchange traffic information and working state, and then collaborate to determine the optimal BS working mode. The neighboring BS negotiation assisted Detection and Analysis steps greatly reduce the complexity and the cost for working mode switch. The full consideration of all network states has the exponential complexity with the network size, while with CHORUS, we are able to reduce it to linear scaling [13]. Next, the *Control Decision* step is realized based on dynamic programming with the per-stage cost at stage i

$$g_i = \sum_{m=1}^{M}\left[\left|s_i^m - u_i^{(m)}\right| E_i + C_s u_i^{(m)} + h\left(\tilde{P}_i^{(m)}\right)\right], \qquad (1)$$

where $s_i^{(m)} \in \{0, 1\}$ is the BS working state, $u_i^{(m)} \in \{0, 1\}$ is the action of BS m, and $\tilde{P}_i^{(m)}$ is the blocking probability of a new call arrived in cell m. So the per-stage cost is a combination of operation energy $s_{i+1}^{(m)} E_i$, switching cost $C_s u_i(m)$ and blocking probability penalty $h(\tilde{P}_i^{(m)})$ of all

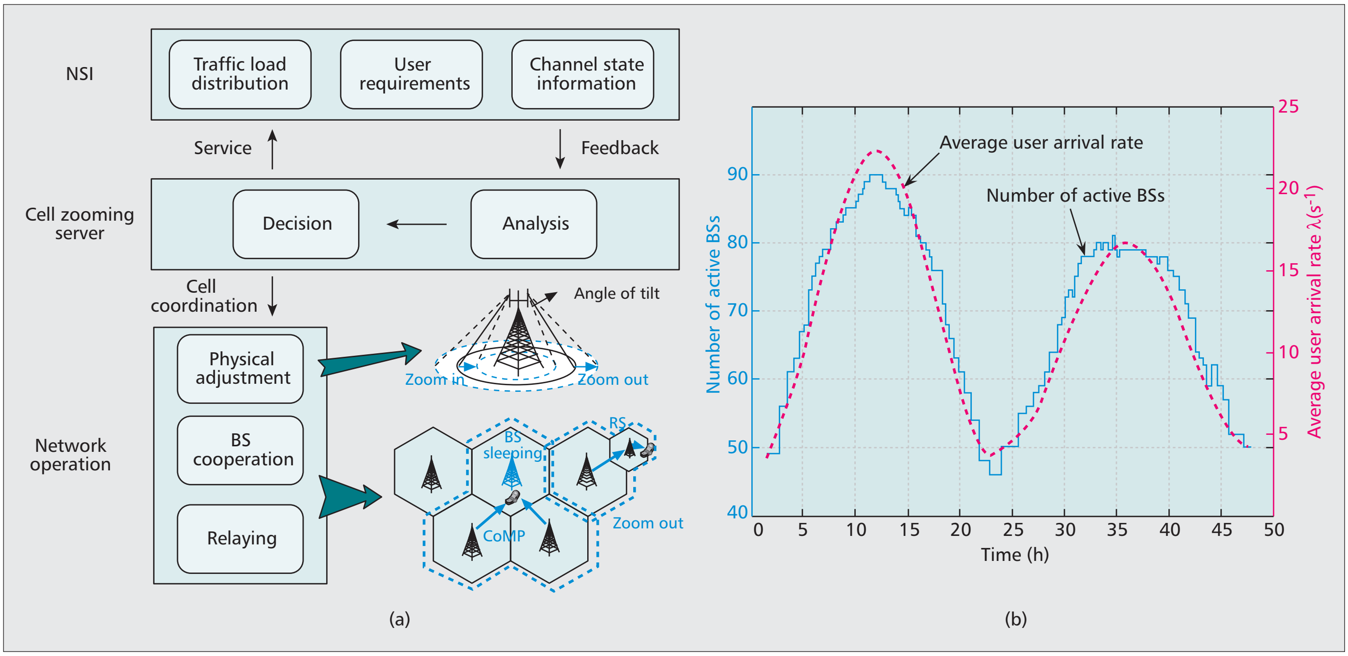

Figure 4. *CHORUS application for smart dynamic BS energy saving: a) architecture of cell zooming under the CHORUS framework; b) number of active BSs compared with the traffic intensity over a two-day period.*

the cells. The objective is to find the optimal policy that minimizes the total cost of all stages

$$\left\{u_{i,opt}^{(m)}\right\}_{i=0,\ldots,N-1}^{m=1,\ldots,M} = \arg\min_{\left\{u_i^{(m)}\right\}_{i=0,\ldots,N-1}^{m=1,\ldots,M}} \sum_{i=0}^{N-1} g_i. \quad (2)$$

The optimal decision of each BS is approximated as a function of local cognition results of the traffic in its own coverage as well as its first-tier neighboring BSs. An iterative algorithm is proposed to find the sub-optimal decisions. The network energy consumption, represented by the number of active BSs, well matches the traffic intensity as shown in Fig. 4.

Ubiquitous Radio Access for Heterogeneous Networks

Scalable collaboration can happen not only intra-system, but more importantly in an inter-system way to provide ubiquitous access. Ubiquitous is identified and articulated as a new computing paradigm, where the network is connected anywhere, any time and with any object. Current user equipment devices are capable of re-configuration to access multiple networks with different protocols. While at the network side, the independent design hinders the open access. The implementation of such network highly depends on the *virtualization* of the network resources and dynamic re-configuration of terminals and networks. When the collaboration happens between different networks, traffic can be splitted and conveyed over heterogeneous networks smoothly. In this section, we will show how the Detection, Analysis, and Decision steps in CHORUS support the reconfiguration of existing networks with minimum cost and with fine time granularity, so that ubiquitous interconnection is realized with optimal radio, power, time-slot allocation at any time, any place.

One application is the integration of communication and broadcast networks (ICBN) [14]. The key issue of ICBN is how to combine advantages of the two types of radio networks, so that an efficient provision of high quality multimedia services is ensured. The cognitive engine identifies the equivalent resource occupancy of delivering certain amount of information bits from any of the two networks. Then downlink data is intelligently delivered through broadcast network or retransmitted through the communication network. One can thus achieve higher spectrum efficiency and thus system capacity.

In ICBN, contents can be distributed to different transmission nodes closer to users. The contents are firstly cached at these nodes before an appropriate choice of the time to broadcast or multicast to users within its coverage. For example, when relay stations (RSs) are introduced, caching with multicast can also help reducing the transmission cost if the need for the same content of different users spreads over time [15]. In some content delivery services such as video-on-demand service, multiple requests of the same content induce redundant traffic if the delivery is naive unicast.

However, as users may appear or request the content at different time, introducing relay caching can replace the power consuming retransmissions from the BS with low power short distance transmission. A single cell in a cellular network with RSs is depicted as Fig. 5. When a user requests a piece of content, the BS may transmit the content to the user directly or may broadcast the content to both the RSs and the user. Contents can be cached into the buffer of RSs in order to serve the nearby users with future requests of the same content. When a piece of content that has already been cached in

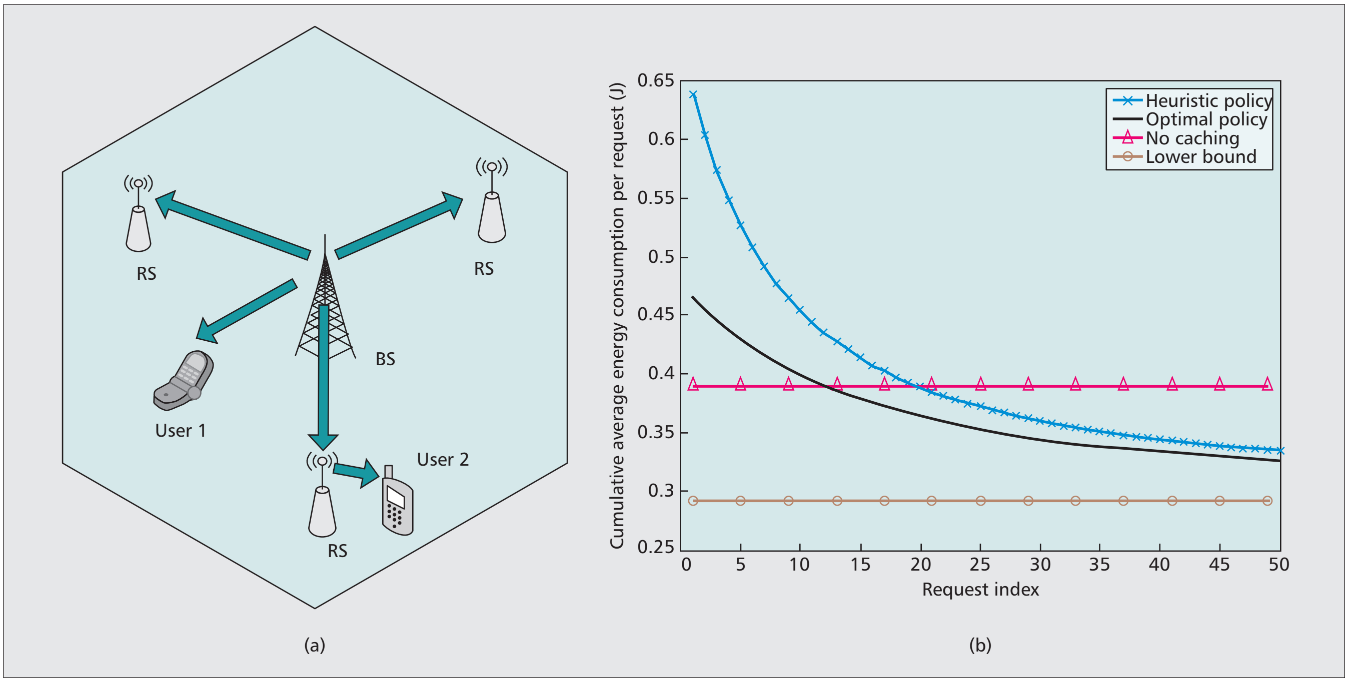

Figure 5. *CHORUS application for smart caching assisted by relays: a) the relay caching scheme in a cellular network; b) average transmission energy consumption per request of the first* i *requests, where we compare the optimal policy and a proposed heuristic with the baseline policy without relay caching, and the energy consumption lower bound is achieved when all the necessary contents are prestored in the relay.*

an RS is requested by a user in the RS's coverage, it can be transmitted from the RS to the user directly.

For this kind of dynamic caching, the problem is to identify whether or not to cache the requested content in the RS, since the buffer size of RSs is limited and caching may consume extra energy. The probability of a piece of content being requested, i.e., the popularity, is introduced as the key NSI. The popularities of contents in the buffer are stored in the profile database, and the cognitive engine makes the Control Decision to determine whether to cache a newly requested content or not. As the system runs, the cognitive engine learns and reconfigures the optimal caching policy through stochastic dynamic programming. The average per request energy consumed by the first i requests with the optimal policy and the derived heuristic policies are shown in Fig. 5. Energy consumption is saved by 15.3 percent after the current caching period of interest starts.

Conclusion

For the ease of constructing ubiquitous and open access wireless systems with large-scale collaboration capability, the conceptual framework called CHROUS is proposed. Current collaborative communication schemes only apply for limited fields, mainly due to the challenges of mass information collection and exchange overhead. CHORUS, on the other hand, aims to solve these issues with cognitive synergy. Compared to conventional cognitive radio, cognition in CHORUS has broader targets, from spectrum and CSI to NSI. The cognition behavior interacts with node collaboration to provide scalable NSI collection and network self-organization. The flexible realization of CHORUS combines local sensing with negotiation among network nodes, and thus efficient virtualization of network resources is realized. The cognitive synergy in CHORUS is illustrated through examples based on our initial research efforts.

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Biographies

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SHIRO TANABE [SM] is in charge of research activity in China as President of Hitachi (China) Research and Development Corporation. Since he joined Hitachi in 1978, he has been engaged in telecommunication and network area in Central Research Laboratory of Hitachi. His research contributions cover multiple fields, including ATM switching, Intelligent Network, large-scale IP network, IPv6 router and 3G/Beyond mobile network, etc. He once was the director of information system research laboratory in Central Research Laboratory of Hitachi. He has been serving as the council member of IEICE. He is a council member of IEICE.