POINT OF VIEW

Heterogeneous Networking: An Enabling Paradigm for Ubiquitous Wireless Communications

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It is a widely accepted notion that the long-term aim of the technological progress in the field of wireless communications is constituted by the provision of *ubiquitous connectivity* between individuals, as well as a multiplicity of existing and future pervasive devices which increasingly permeate our environment.

In this context the currently dominant cellular (a combination of metropolitan, local, and personal area networks—MANs, LANs, and PANs, respectively), as well as the emerging mobile ad hoc network (MANET) architectures constitute the two major contenders for the role of systemic paradigm, which would facilitate the realization of ubiquitous wireless networking. The corresponding literature offers an extensive body of theoretical as well as experimental work [1]–[3] advocating the potential advantages of either of the two aforementioned approaches.

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Against this background, we would like to maintain that in order to achieve the required level of integration, performance and efficiency, the future telecommunications technology may have to infer cues from the structural characteristics of the human society itself. Correspondingly, in this paper we would like to consider some of the relevant aspects of the societal constitution, which may hold crucial clues to identifying the promising avenues towards further technological advancement.

More specifically, in this paper we explore the principle of heterogeneous wireless networking, constituted by the fusion of classic cellular and ad hoc network topologies. Specifically, we would like to maintain, that the *heterogeneous* network inherits the vital complementary characteristics of both aforementioned architectures, and thus has the potential of attaining the levels of performance and efficiency required by the future wireless communications.

II. UBIQUITOUS WIRELESS NETWORKS

A. The Heterogeneous Nature of Social Organization

We would like to identify two major complimentary ingredients in the composition of the modern society. On the one hand, the societal structure is constituted by multiple layers of large-scale infrastructure, which may be associated with the various facets of the human activities. Such infrastructure layers include, for example, the transportation networks composed of multiple subnetworks, including land, sea, and air transportation systems. Other examples of societal infrastructure include the educational system, healthcare system, legislative and jurisdictional systems, banking system, etc. We may safely establish that the foremost merits of such systems lie in their robustness, reliability, and predictability. The deployment of such systems typically involves a top-down design methodology, systematic planning, as well as a strictly hierarchical approach to their management and maintenance. Ultimately, these systems are typically governed by a set of well established and explicitly formulated rules.

On the other hand, the human society is animated by the layer of personal ad hoc interactions among individuals. The nature of such interactions is decidedly different, and often opposed to that, pertaining to the interactions occurring within the infrastructure layers. Specifically, the individuals are capable of establishing temporal ad hoc links with each other, depending on the specific context of their daily activities. Furthermore, in contrast to the infrastructure-bound interactions, the interpersonal interactions rely on an implicit code of informal rules and behavioral practices.[1]

In order to further emphasize the distinctive, yet complementary roles of the two aforementioned constituents of the social organization, we would like to invoke the terminology devised in [4], where we discuss the inherent dichotomy between the notions of system's *efficiency* and its *efficacy*. Specifically, in [4], we define *efficiency* as the ratio between the quantities describing the desired and the total outputs of some productive system. Subsequently, we define *efficacy* as the ratio between the attained amount of the desired output and some nominal amount, which the system considered was conceived to attain.

For example, a conventional incandescent light bulb is highly inefficient, since most (about 90%) of its output is constituted by heat, rather than the desirable product in the form of visible light. On the other hand, the conventional incandescent light bulb may be categorized as highly effective, since the objective of providing an adequate illumination using this device may be readily realized. In contrast, a light-emitting diode (LED) based lighting system may exhibit a remarkably high *efficiency* at low power levels, where its relative *efficacy* is inadequately low for most mainstream lighting applications [5].

For the sake of this discussion, therefore, we would like to conjecture that while the large-scale infrastructure layers of the social structure may be directly associated with its *efficacy*, it is the diversity, adaptability and the inherent flexibility of the ad hoc personal interactions that make human society *efficient*. Furthermore, the intricate interplay between these two constituents of the societal organization, and the ensuing balance between society's *efficacy* and its *efficiency*, determines the apparent stability and the relative prosperity of a developed contemporary society [6].

Likewise, some of the major problems, which our society is currently facing, including the unsustainable exploitation of the natural resources may be ultimately traces to our preoccupation with the collective and personal *efficacy*, and the associated excessive reliance on the society's infrastructure, at the expense of the *efficiency* of our actions.

In the following sections, we would like to translate our observations concerning the structural composition of the human society into the realm of wireless communication networks.

B. Cellular Versus Ad Hoc

Let us consider the two major networking paradigms, namely the *cellular* and the *ad hoc* network architectures schematically portrayed in Fig. 1(a) and (b). Specifically, the cellular network architecture of Fig. 1(a) is characteristic of the currently prevalent multioperator wireless communication networks [7]. The cellular topology exhibits a strictly hierarchical structure, where the single master node shown at the top of Fig. 1(a) corresponds to the central authority, such as the Federal Commission of Communications (FCC) in the United States, or Ofcom in the U.K., which owns and regulates the usage of the enabling resource constituted by the frequency spectrum. The executive power within the multioperator cellular network is distributed across multiple mutually competitive commercial entities, typically referred to as *service providers*, or wireless carriers, as indicated by the distinctive branches in the network hierarchy of Fig. 1(a). These service providers install, own, and operate a proprietary infrastructure, which utilizes the allocated spectrum in order to generate value for the subscribers and to maximize the corresponding monetary revenue for themselves.

Relatively small fragments of the frequency spectrum are licensed in this context for the exclusive use by a specific network operator. Importantly, two subscribers of the same operator are not authorized to directly utilize the spectrum without invoking the operator's infrastructure. In the context of the network topology of Fig. 1(a), this implies that no horizontal node-to-node interactions between the bottom-level user nodes are possible. In other words, no peer-to-peer cooperation between the network

[1] The social behavioral practices should not be confused with the civil or criminal law, which is a set of explicit rules employed by jurisdictional system in order to resolve conflicts whenever a satisfactory resolution may not be achieved by the individuals themselves.

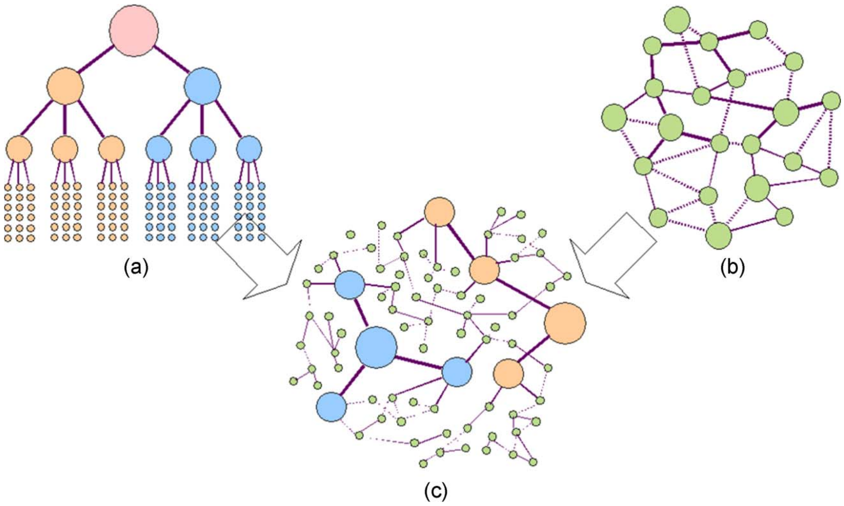

Fig. 1. ***Network architecture. (a) Cellular: scalable and highly dependable architecture designed to maximize efficacy. (b) Ad hoc: flexible, self-organizing architecture designed for maximum efficiency. (c) Heterogeneous: a fusion of cellular and ad hoc architectures, which inherits the advantages of both topologies, and thus attains the desired trade-off between efficacy and efficiency.***

subscribers is allowed. The resultant infrastructure-based network architecture exhibits the highly advantageous properties of centralized control, dependability and scalability.

On the other hand, the MANET architecture schematically depicted in Fig. 1(b) potentially offers a dramatically higher power efficiency, which is facilitated by the structural flexibility and the ability to leverage short-range ultra-low-power communication links. The utilization of the ad hoc networking has been successfully demonstrated by, for example, the One Laptop Per Child (OLPC) project (laptop.org), which utilizes the technology based on the IEEE 802.11s standard [8].

Importantly, a wireless ad hoc network relies on peer-to-peer cooperation, where the mobile terminals utilize peer terminals as relays in order to gain access to the network's infrastructure. Clearly, the necessity of peer-to-peer cooperation suggests a suitable *open access* approach to spectrum management [7], where a substantial portion of the frequency spectrum is made available to the network's end users, as opposed to the network operators in the case of commercial cellular networks. Accordingly, the sharing of the resources, as well as the diverse conditions typically encountered in wireless channels imply a substantial level of control, including elements of resource management, to be delegated to the mobile terminals. The resultant distributed control and resource management capabilities of the mobile terminals may be intricately related to the concept of cognitive radio [9].

Subsequently, we would like to hypothesize that the *heterogeneous network* constituted by the fusion of these two networking models may inherent the advantageous properties of both architectures. The resultant heterogeneous radio access network (HRAN) is depicted in Fig. 1(c). Specifically, the main role of the large-scale cellular infrastructure denoted by large circles in Fig. 1(c) is to assure dependability, availability, and generally the *efficacy* of the network, while the complimentary layer of ad hoc connections may facilitate the desirable flexibility and the associated *efficiency*. In the next section, we would like to detail some of the distinctive properties of the proposed heterogeneous networking paradigm.

C. Heterogeneous Radio Access Network

Following the principles of heterogeneous networking, a mobile terminal may choose among multiple available connectivity alternative, including infrastructure-based, as well as cooperative multihop ad hoc links, based on the criteria of cost-efficiency [10] and suitability for the particular application scenario, while pursuing the objective of dramatically improving the cost- and energy-efficiency of the entire network. Specifically, we would like to emphasize some of the important properties of the resultant HRAN of Fig. 1(c), which exhibits the complementary characteristics of the constituent WLAN and MANET network layers.

Topology: The HRAN architecture considered exhibits the structural properties of a *scale-free network* [6], [11]. In addition to the aforementioned example of contemporary human society, another prominent example of such *scale-free network* is constituted by the World Wide Web (WWW). Specifically, the WWW constitutes a virtual ad hoc network of interconnected multimedia documents, while relying on the physical infrastructure formed by the global Internet [11], which is comprised by a multiplicity of interconnected infrastructure-based networks of various sizes, topologies and purposes.

Scalability: Importantly, as opposed to the infrastructureless ad hoc network discussed in [12], the heterogeneous network architecture of Fig. 1(b) contains a relatively small number of ad hoc nodes per single node of the infrastructure, thus facilitating the seamless scalability of the cellular architecture, and avoiding the per-node capacity degradation of the ad hoc architecture potentially inflicted by excessive relaying, as formulated by the Gupta–Kumar law [12].

Adaptability: As opposed to the cellular architecture of Fig. 1(a), the heterogeneous network of Fig. 1(b) exhibits the desirable properties of adaptability and self-organization, where the average range of the communication links and their respective power efficiency is determined by the density of the network users. Observe that in an adequately designed HRAN, which employs an appropriate method of power control, spectrum sensing, and frequency reuse, the amount of the frequency spectrum required is independent of the number of end users.

Spectrum Management: The resultant heterogeneous networking model is likely to require a combination of licensed and unlicensed spectrum access models reminiscent to that existing today [7]. We would like to hypothesize, however, that in contrast to the currently prevailing spectrum management policy, a substantial increase in the amount of spectrum allocated for the unlicensed access will be required in order to facilitate an interference-free layer of broadband ad hoc connectivity.

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