Cognitive Networks: Standardizing the Large Scale Wireless Systems

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***Abstract*— [1] State-of-the-art research and development in large-scale wireless systems have been pushed to the limits, essentially on dealing with the challenges from network scalability and node resource (complexity) constraints, as well as the need for an effective application programming interface. In this paper, we present the reference model of Embedded Wireless Interconnect (EWI), as a potential merge of research advances in multiple engineering disciplines, so as to effectively encapsulate the complexities of large-scale wireless networking. The cognitive radio approach is applied in the EWI reference model, where we define two basic propositions of the cognitive radio for large-scale wireless networks, i.e., opportunistic spectrum sensing and polling, respectively. The research suggests the potential standardization of the cognitive radio in large-scale wireless systems, which consequently results in the *large-scale cognitive networks*, opportunistically utilizing network resources including both spectrum bandwidth and wireless node availability, and achieving effective application programming over such systems.**

I. Introduction

Although large-scale wireless systems have been envisioned with a lot of promising applications, including wireless sensor networks [1] (e.g., industrial or scientific monitoring), wireless mesh networks [5] (e.g., municipal WiFi mesh), the development and programming of such applications have been full of challenges. Start-of-the-art technologies have been pushed to the limits, essentially on dealing with the requirements of network scalability and node resource (complexity) constraints, as well as the need for effective application developing.

In system engineering, related researches have been conducted for the application programming interface, i.e., the middleware design [6], for distributed computations. Many researches in the area, e.g., TinyDB [7], Cougar [8], EnvioTrack [9], have indicated the need for application specific network design in dealing with the Quality of Service (QoS) of target applications, as well as the requirements of network scalability and node complexity. However, it is also understood that the dependence on holistic design may indeed hamper the potential mature of middleware technologies, since the design modularity may not be well maintained.

In network engineering, related researches have largely originated from general-purpose Mobile Ad-hoc Networks (MANET) [10], [11]. Essentially, the Medium Access Control (MAC) layer configures logic wired links over wireless medium, on which ad-hoc routing protocols run over a predetermined network topology in the network layer. On top of that, the transport layer is expected to set up end-to-end tunnels for general-purpose applications. Although this model has been working fine in traditional computer networks, including the current Internet, difficulties have been arising in large-scale wireless networking, where the network design could not handle both random application traffic and random wireless propagation fading simultaneously. Consequently, although MANET related researches have been of over ten years, there have also been very limited implementations of multihop wireless in engineering practices. It is worthwhile to note a number of recent initiatives, deviating from the MANET paradigm, e.g., Oppnets [12], Haggle [13], Bionets [14]. However, they are now more likely trimmed to special applications, instead of providing system designers with re-usable network abstractions.

In the engineering discipline of radio communications, researches are now being concentrated on the concept of cognitive radio. Cognitive radio was firstly proposed in [15], where the radio is envisioned with the intelligence to exploit ambient environment for user centric communications. With the support from regulation authorities, e.g., FCC (Federal Communications Commission) in the United States, who have recognized the inefficiency of legacy static spectrum allocation, cognitive radio researches have then been focused on the capability of opportunistic spectrum access [16], [17]. Existing researches in the networking of cognitive radios are however still at an infancy stage, where most engineering developments have been conducted for single hop infrastructure networks, e.g., IEEE 802.22 WRAN (Wireless Regional Area Networks) [18].

In this paper, we first present the reference model of Embedded Wireless Interconnect (EWI) [2]–[5], which could offer a possible converge of research advances in multiple engineering disciplines. EWI provides for flexible network abstractions to system designers, so as to realize effective application programming in large-scale wireless systems. The model also resolves the challenges of network scalability and individual node resource constraints. Particularly, it has been demonstrated that [2] *the system performance can improve with larger network scale, whereas the complexity at individual nodes can be independent of any network scale*. Moreover,

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EWI provides for an architecture of the large-scale networking with cognitive radios. We then define two basic cognitive-radio propositions for large-scale networks, which are opportunistic spectrum sensing and polling, respectively.

Our investigation indicates the need for standardizing the cognitive radio in large-scale wireless systems, conforming to the EWI architecture reference model, so as to reach possible industrial proliferation. This standardization should result in the *Large-scale Cognitive Networks*, where the wireless network can intelligently adapt to ambient environments, and collaboratively achieve application-centric functionalities, by *the opportunistic utilization of network resources including both spectrum bandwidth and wireless node (radio) availability*.

II. Embedded Wireless Interconnect

The innovation of the EWI reference model starts with the redefinition of wireless linkage. Instead of configuring logic wired links over wireless medium, it defines the *abstract wireless linkage*, which is arbitrary abstraction of wireless node cooperation in proximity range. EWI further adopts the following three principles.

A. Principles

First, the abstract wireless linkage is based on functional abstractions of proximity node cooperation, where the categories can include: broadcast, unicast, multicast, and data-aggregation wireless links, etc. *Wireless link modules* are designed as the building blocks at individual nodes, implementing different types of abstract wireless links. The principle decides the basic architecture of EWI, which is comprised of two layers. The bottom Wireless Link layer supplies a library of wireless link modules to the upper System layer; and the System layer organizes the wireless link modules for achieving effective application programming.

Second, typical random wireless-networking conditions are opportunistically exploited so as to achieve reliable communications. Some of these random conditions are: a) node availability, introduced by deployment, mobility or congestion etc.; b) wireless channel/bandwidth availability, determined by wireless fading and interferences; c) unpredictable traffic load; d) variable power supplies, e.g., solar power. The principle decides the design methodology of wireless link modules, where the set of nodes joining in an abstract wireless link is opportunistically formed, based on opportunistically available spectrum. Intuitively, the system performance should improve with larger network scale, since a larger number of nodes can introduce higher diversity to be exploited in the abstract wireless link formation.

Third, global application and/or network level QoS is statistically decoupled into local requirements of proximity node cooperations, i.e., the QoS of abstract wireless links. By decoupling application level QoS, the System layer can decide how to organize the provided wireless link modules [4]. By decoupling network level QoS, the QoS design of wireless link modules can be achieved, subject to the dataflow requirements such as throughput, end-to-end delay, and delay variance [3]. Intuitively, complexity at individual nodes can be independent of any network scale, based on the provided wireless link modules.

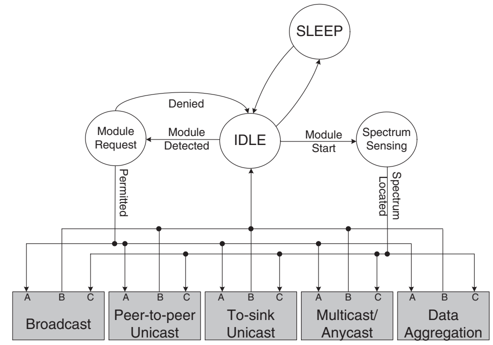

Fig. 1. State Diagram of the Wireless Link layer

B. Library of Wireless Link Modules

We suggest that the EWI reference model can contribute to a converge of the system, network, and radio engineering. The wireless link modules provide for reusable open network abstractions to system designers, where individual modules can be updated, inserted into, or removed from the Wireless Link layer, subject to the requirements of middleware or application developments.

Fig. 1 shows an exemplary state diagram of the Wireless Link layer, where the library of wireless link modules is illustrated. Four states are shown, which are the SLEEP, IDLE, Module Request and Spectrum Sensing states, respectively. The Wireless Link layer remains in the IDLE state if no wireless link module is invoked. Certain primitives are provided for the switching between the IDLE state and the SLEEP state, which is of a further power saving mode. During the IDLE state, the Wireless Link layer monitors the initiations of abstract wireless links. On detecting any wireless link initiation from surrounding nodes, the Wireless Link layer transfers from the IDLE state to the Module Request state, where the request for joining in the abstract wireless link is sent to the System layer. Upon receiving the response, the Wireless Link layer either transfers back to the IDLE state, or invokes the corresponding wireless link module. The other way of invoking wireless link modules is by receiving a command from the System layer, where the Wireless Link layer transfers from the IDLE state to the Spectrum Sensing state. A corresponding abstract wireless link is initiated after appropriate spectrum resource has been located.

Five exemplary types of wireless link modules are shown in Fig. 1, of which the embodiments will be further described in Section III. There are two further procedures in Fig. 1, which are "spectrum sensing" and "module detecting", respectively. The implementations of them are dependent on the radio, which will be elaborated in the following.

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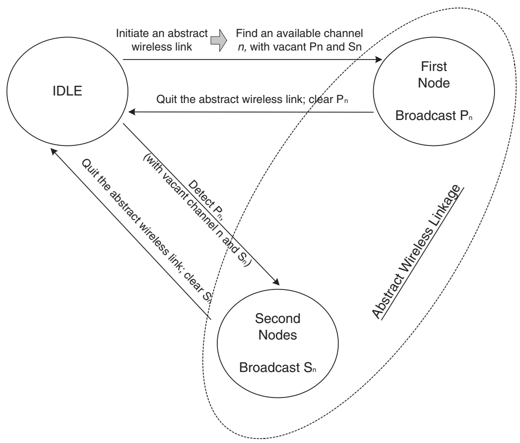

Fig. 2. State Diagram of the Cognitive Radio

C. Cognitive Radio Propositions and Prototyping

Two basic cognitive-radio propositions are defined for large-scale wireless networks, which are comprised of the opportunistic "sensing" and "polling", respectively:

1) Sensing: the radio can opportunistically sense available spectrum resource, and the selected spectrum will not be interfering with other co-existing wireless communications.
2) Polling: the radio can opportunistically poll proximity radios onto the selected spectrum, so as to realize certain types of local cooperations.

In the context of EWI, a wireless node with the defined cognitive radio can initiate an abstract wireless link, where both the spectrum usage and the participating wireless nodes are opportunistically decided, based on the availability. The initiated abstract wireless link will not be interfering with other co-located wireless communications, protected by the first cognitive proposition.

We further describe an exemplary implementation and the first prototyping [2], [3], based on the two cognitive radio propositions. Assume that there are N data channels differentiated by frequency, time, or spread codes, where every data channel n is associated with two distinctive frequency tones, which are one sensing tone S_n and one polling tone P_n, respectively. On initiating an abstract wireless link, the first node senses for an available data channel n, where both the sensing tone S_n and the polling tone P_n are also vacant. The first node then broadcasts the polling tone P_n, to poll surrounding nodes. On detecting the rising edge of P_n, the surrounding nodes can decide whether to join in the abstract wireless link on the data channel n. On joining in the abstract wireless link, the surrounding nodes become the second nodes of the link and broadcast the sensing tone S_n. Hence, both the sensing and polling tones protect the abstract wireless link from interferences.

A diagram of the described implementation is shown in Fig. 2. Compared to Fig. 1, Fig. 2 has the same IDLE state. The state of First Node in Fig. 2, and the related transferring branches, represent the procedure of initiating an abstract wireless link, which are also shown to the right of the IDLE state in Fig. 1. The state of Second Nodes in Fig. 2, and the related transferring branches, represent the procedure of joining in an abstract wireless link, which are also shown to the left of the IDLE state in Fig. 2. Current prototyping and experiments are described in [3], in which the radio prototype is comprised of two transceivers. A pilot transceiver is dedicated to the detection and transmission of frequency tones; and a data transceiver is dedicated to the data transmission and receiving. It has been observed that the prototype works well in the unlicensed 2.4GHz band, despite uncoordinated interferences, e.g., from adjacent WLAN (Wireless Local Area Networks) hot zones.

III. MODULE EMBODIMENTS

Some working embodiments of wireless link modules are described here, which include the broadcast, peer-to-peer unicast, and data aggregation modules. We have been implementing these embodiments in our prototyping, so as to program the applications in large-scale wireless systems [2]. Other arbitrary types of wireless link modules may be envisioned, subject to application and/or middleware requirements. For example, the to-sink unicast module utilizes higher capabilities of the sink in terms of power, computation, or storage, to improve data delivery, which may be useful in wireless sensor networks. The multicast module delivers data to multiple destinations as compared to the peer-to-peer unicast module, which can be useful in the applications of IPTV.

A. Context Address and Cost of Delivery

Different from IP (Internet Protocol) address or MAC address, the network address within the EWI reference model is based on context, e.g., location coordinates, application specific address, or logic address, etc. Therefore, a wireless node can acquire more than one addresses according to the contexts. Some neighboring wireless nodes can also share the same context address if they are regarded as identical for particular context. Furthermore, a *cost of delivery* criterion is applied to the context-based network addresses in the design of wireless link modules, which can be necessary in order to decouple global network QoS. Particularly, an estimated cost of sending one data packet (information unit) from a node n with the address $\mathbf{C}_n$ to a node m with the address $\mathbf{C}_m$, can be directly calculated from $\mathbf{C}_n$ and $\mathbf{C}_m$, which is denoted by $c_{m,n}$. In location-centric networks, where wireless nodes are aware of their own location, the network address is of the node's location coordinates. Therefore, the cost of delivery $c_{m,n}$ is determined by the distance $c_{m,n} = |\mathbf{C}_m - \mathbf{C}_n|$. In data-centric networks, e.g., [19], the application-specific context decides the network address. The cost of delivery depends on data gradient, which is also correlated to the proximity between the nodes n and m. In data collecting or fusion

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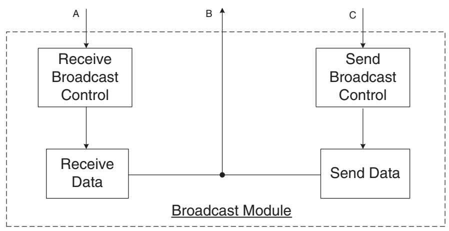

Fig. 3. State Diagram of the Broadcast Module

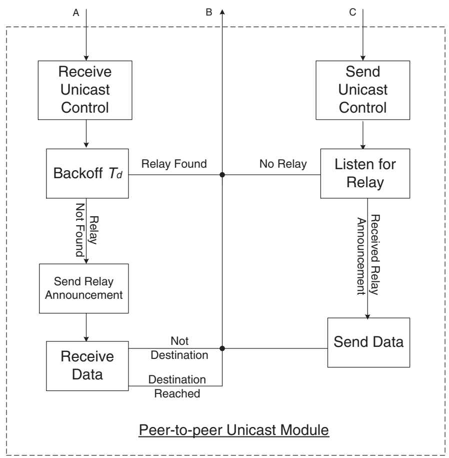

Fig. 4. State Diagram of the Peer-to-peer Unicast Module

networks, for example, wireless sensor networks, the sink or data collector can broadcast identity advertisements, which are thereon flooded in the network. On receiving the advertisement packets, every node can count the average smallest number of hops to the sink, which can be used as the cost of delivery.

B. Broadcast Module

Fig. 3 shows an exemplary state diagram of the broadcast module, in which the ports *A*, *B*, and *C* conform to the illustration in Fig. 1. The broadcast module simply realizes the broadcasting and receiving of data packets. We also note that some broadcast control information is sent before the data, e.g., the source address and the QoS control. The broadcast module QoS can be determined by broadcasting range and/or latency. Particularly, broadcasting range is the maximal required cost of delivery from the source node; whereas broadcasting latency indicates the data urgency. The module uses the combination of the two requirements to decide the optimal power and rate control, i.e., resource allocation.

C. Peer-to-peer Unicast Module

Fig. 4 shows an exemplary state diagram of the peer-to-peer unicast module, while extensively studies with analysis, simulation, and experiment results have been reported in [3]. The peer-to-peer unicast module sends data packets from source to destination, where the opportunistic selection of relay nodes is implemented. The unicast control information includes the source address, the destination address, the data-sender (current relay) address, and the QoS control. When

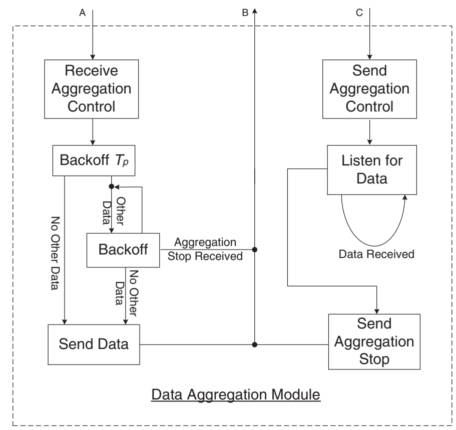

Fig. 5. State Diagram of the Data Aggregation Module

the control information is received, the relay candidates, i.e., the nodes joining in the unicast wireless link, can locally calculate a time-delay parameter T_d, decided by the cost of delivery to the destination, as well as the wireless channel status. The relay candidate with satisfying wireless channel and the smallest cost of delivery, should obtain the smallest T_d. This favored node then broadcasts a relay announcement packet, and serves as the next-hop relay by receiving the data. If the next-hop relay is not found, the current relay (data-sender) can re-send the data. We also note that a resolution procedure may be further employed, if more than one relay candidates obtain the same smallest T_d. The unicast module QoS is determined by the dataflow requirements of throughput, end-to-end delay, and delay variance. It has been shown in [3], that these global network QoS can be supported in peer-to-peer unicast module design, by transmitting power control (or joint power and rate control).

D. Data Aggregation Module

Fig. 5 shows an exemplary state diagram of the data aggregation module. The aggregation node can use this module to collect context-related data packets from proximity nodes. Here, the aggregation control information includes the aggregation address, i.e., of the aggregation node, and the context request, e.g., measurement metrics related to certain events. The module QoS is determined by the data quality related to the requested context, where data with higher quality should obtain higher priority for being sent to the aggregation node. A time-delay parameter T_p is then calculated at the nodes joining in the aggregation, which is the backoff period inversely proportional to the data quality. If the channel is busy after this backoff period T_p, i.e., another context-related data packet with higher priority is being transmitted by another node, the current data at local node is subject to another fixed-period backoff, decided by the transmission time of one data packet. In consequence, context-related data packets should be broadcasted to the aggregation node sequentially according to the data quality. After enough data has been received, the aggregation node broadcasts an "aggregation stop" control

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packet to terminate the data-aggregation wireless link. Therefore, data-aggregation wireless links are opportunistic for applications, where the best-quality data is collected, according to the requested context. It has also been shown in [4], that the optimization between application QoS and network energy consumption can be formulated and addressed at the System layer, by a control knob in middleware implementation.

IV. Cognitive Networks in Large Scale

As the technology matures with the EWI reference model, we would suggest the possible standardization of some typical wireless link modules, with the defined cognitive-radio propositions. Such standardization can be important in terms of offering an universal communication language for large-scale wireless systems. In consequence, we arrive at the *large-scale cognitive networks*.

Therefore, the concept of large-scale cognitive networking is to opportunistically utilize network resources including both spectrum bandwidth and wireless node (radio) availability, so as to establish effective applications over large-scale wireless systems. From previous discussions, we have shown that the implementation of this concept can be realized by adopting the EWI reference model, with the implementation and organization of abstract wireless linkage.

Moreover, as identified in [20], the capacity of wireless networks is generally decided by the order of $O(\sqrt{N} \cdot B)$, where N is the number of nodes (radios), and B is the spectrum bandwidth. Since cognitive networking opportunistically utilizes both types of resources, it could offer (virtually the only way according to our investigations) to approach the capacity of wireless networks, under random networking conditions where the availability of both spectrum and wireless nodes can not be predetermined, e.g., due to random networking conditions such as interferences and/or congestions, etc.

V. Conclusion

Two keystones have been revealed in our discussion of the EWI reference model. First, it centrally resolves the challenges of network scalability and individual node resource constraints (complexity) in large-scale wireless systems. Second, it can provide for flexible network abstractions for effective application developments, i.e., by the wireless link modules, where individual modules can be added, updated, or removed, in accordance with system design requirements of middlewares or applications.

In conclusion, compared to traditional computer networks, where the industrial success begins with the development of individual systems (e.g., Personal Computer), the possible industrial proliferation of large-scale wireless systems should start with enabling network technologies, since any application on top cannot be afforded by a single node but needs the mass collaboration among all. Analogous to the TCP/IP stack, which offers a scalable language to general-purpose computer networks, we suggest that the standardization according to the EWI reference model can offer similar benefits to the cognitive networks in large scale. The new architecture can then be integrated with existing deployments as well (e.g., shown in [5]).

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