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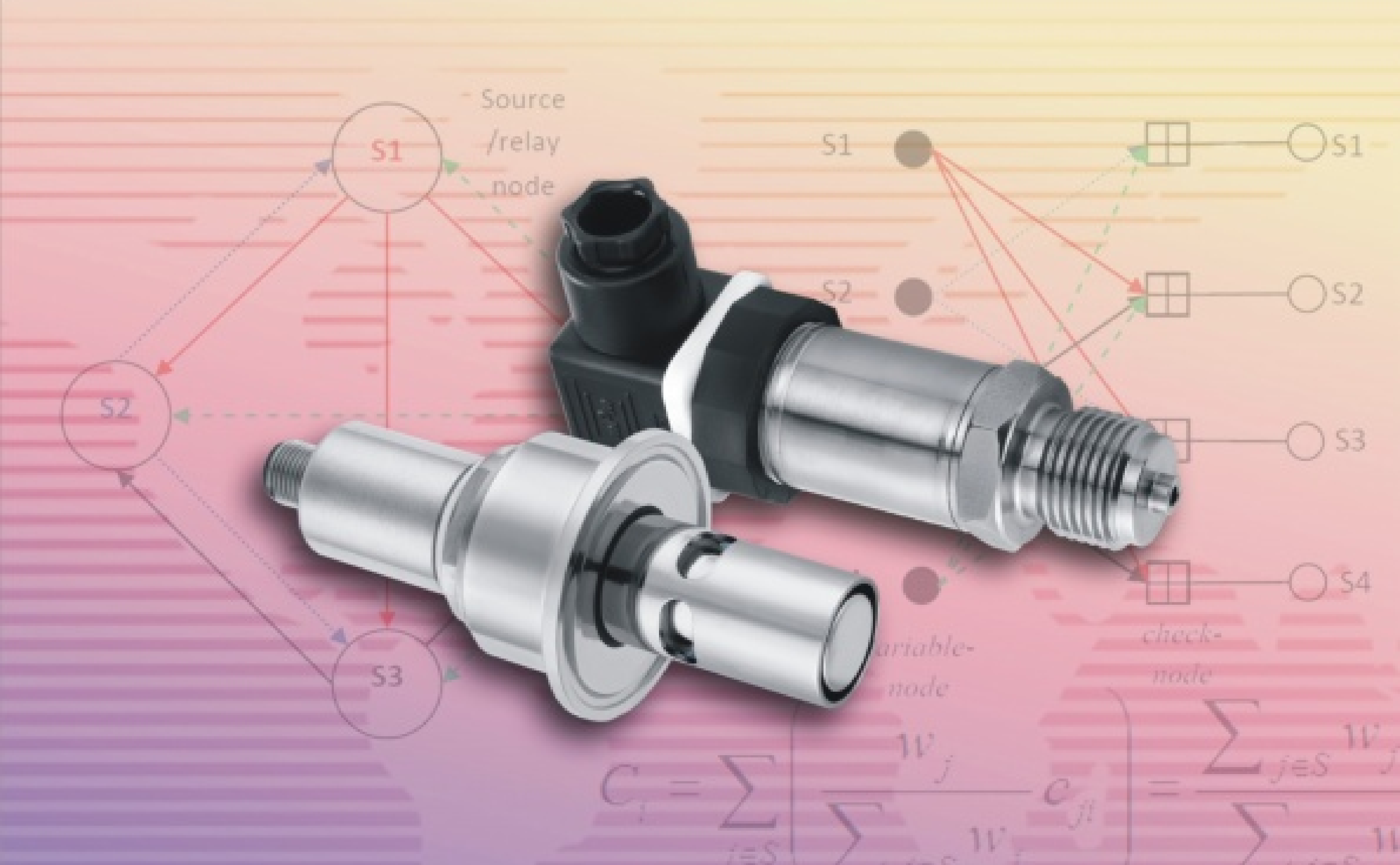

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Sergey Y. YURISH

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Heterogeneous Network Convergence with Artificial Mapping for Cognitive Radio Networks

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Abstract: The artificial mapping scheme is proposed in this paper for adaptive network collaboration of cognitive radio networks. The superiority of the DHT-based overlay for its link state aggregation property, which establishes global convergence for link state aggregation message among a scalable number of nodes, is considered in the analysis. In addition, the fuzzy logic inference can better handle uncertainty, fuzziness, and incomplete information in node convergence report, which is developed as a novel approach to aggregate wireless node control with affordable message overload. The Artificial Mapping Tree (AMT) for the new convergence scheme is verified by the simulation and experimental results. The moderately increased network throughput for convergence validation is demonstrated with the proactive spectrum coordination. *Copyright © 2013 IFSA.*

Keywords: Leave cognitive radio networks, Heterogeneous architecture, Artificial mapping, Fuzzy logic inferences, Dynamic resource management.

1. Introduction

Cognitive radio is a revolution in radio technology that seeks to overcome the spectral shortage problem by enabling secondary wireless devices to communicate without interfering with the primary users [1, 2]. In a cognitive radio network (CRN), each node is equipped with a cognitive radio, which employs cooperative relay technology for increasing transmission diversity gain in various types of wireless networks [3]. Such cooperative relay between secondary nodes can improve spectrum diversity and thus, a CRN dynamically adapts to varying network conditions in order to optimize end-to-end performance in a distributed environment [4]. In addition to dynamic spectrum access, cognitive radio's spectrum-rich node is selected as the relay node to improve the performance between the source and the destination. It is envisioned that CRN will be accepted as a general radio platform upon which numerous wireless applications can be implemented.

It is important to realize that CRN will provide high bandwidth to mobile users via dynamic spectrum access techniques and heterogeneous wireless architectures. Also, decisions in terms of control and data are made to meet the requirements of the network as a whole, rather than the individual network components. These important end-to-end architecture issues warrant that heterogeneous network convergence for a CRN is more complex and interesting. In addition, a fundamental problem for a wireless network is spectrum etiquette. In a multi-hop wireless network, spectrum etiquette is challenging since it utilizes and shares spectrum resources by allowing wireless devices to exchange appropriate messages and parameters. When CRN is allowed to perform spectrum etiquette, the problem becomes even more difficult due to its adaptability of collaborating radios. Consequently, the adaptive network collaboration is expected to provide significant performance gains in dense usage scenarios.

In this paper, the artificial mapping problem is introduced and studied in heterogeneous CRN. The goal is two-fold. First, the problem is aimed to formalize with respect to resource management that defines the nature of available spectrum of various applications. Based on this control plane aggregation framework, guidelines that can provide significant performance advantages in dense or clustered radio environments are derived. Second, a new DHT-based control plane based on fuzzy logic inference, FuzzyConvergence, is proposed and analyzed, thereby establishing global convergence among a scalable number of wireless nodes. Specifically, the following contributions are made as follows:

- An artificial mapping framework is developed for dynamic spectrum allocation in CRN. The framework captures the essential features of cognitive radios, such as frequency agility and adaptive bandwidth, and it introduces the mechanism of an Artificial Mapping Tree (AMT), which is built on top of a generic DHT. This method is used to define the resource management problem as the fuzzy logic inference for link state aggregation, such that the demands of all nodes are satisfied best possible. Our model represents a fundamental departure from the conventional analysis framework that handles uncertainty, fuzziness, and incomplete information for maximizing spectrum usage.
- A primary service selection algorithm is presented, it weight all available primary services and allocate other secondary services within a small constant factor of the optimum, regardless of network topology. This offers us the artificial mapping connections of using policy selector.
- FuzzyConvergence is proposed as a practical, distributed method to solve the adaptive network collaboration problem in real cognitive networks. FuzzyConvergence enables each node to dynamically decide on an affordable message overhead based only on local information. Using both analysis and extensive simulations, it is shown that FuzzyConvergence achieves high network throughput and short convergence time under various scenarios.

2. Related Work

There have been active research efforts on distributed spectrum coordination for wireless networks resource management. In [5], a network-coded cooperative communications as new paradigm is proposed, which combines sessions into separate groups, and then has the source node of the new session select the best group among all offers, concerning selecting the most beneficial relay node. In [6], the authors investigate a distributed technique for dynamic spectrum management of DSL lines, and generalize several known techniques, by imposing pricing for use of spectrum. In [7], a distributed coordination approach without relying on the existence of a pre-assigned common control channel is proposed by upgrading the legacy protocol stack for robust operation under network dynamics. However, little work has been carried out for artificial mapping with heterogeneous network in response to changes in adaptive wireless networks environment or changes in application requirements simultaneously.

Exploiting network convergence in wireless multi-hop networks has attracted enormous interests in recent years. In [8], the authors describes that wired broadband access networks to continue to evolve toward a common general-purpose platform architecture, while wireless networks to remain heterogeneous, with many of them specialized to particular wireless services. In [9], the authors show how to use EPON as a backhaul to connect multiple dispersed WiMax base stations. They built upon integrated architectures taking advantage of the bandwidth benefit of fiber communications, with regards to mobile and non-line-of-sight features. In [10], the authors develops a vertical handoff decision algorithm that enables a wireless access network to not only balance the overall load among all attachment points and Access Points, but also to maximize the collective battery lifetime of Mobile Nodes. Furthermore, our technique requires a broad set of wireless network convergence input factors, including artificial mapping and DHT-based overlay structure.

On another line of research, various efforts have been made to study fuzzy logic inference of wireless networks application (see, *e.g.*, [11-13]). These efforts differ from ours in this paper, which focuses on designing network convergence for a finite-sized network.

3. Heterogeneous Networks with Fuzzy Logic Inference

3.1. Artificial Mapping Systems Architecture

Fig. 1 presents the key components of a typical cognitive radio networks artificial mapping system. In this figure, solid lines link the intended exchange partners and symbolize the establishment of mutual convergence. The dashed lines refer to intermediate nodes involved in the control aggregation process. The system is built with a P2P overlay network to facilitate artificial mapping over the IP backbone. With regard to the autonomous nodes which are involved, heterogeneous convergence for cognitive radio networks is spectrum user-oriented.

Dynamically, this system could grow or shrink with self-organizing characteristic.

Consequently, four major cognitive radio networks applications are addressed for the network coordination: spectrum sensing, spectrum allocation, aggregation information sharing, and power control among the distributed environment. With this agility of the radio transceiver, spectrum resource could be shared among licensed (*i.e.*, primary) and unlicensed (*i.e.*, secondary) services to improve spectrum utilization and also to generate higher revenue to the spectrum owner. To support consumer product exchange and share aggregation information, the convergence system is designed specifically, service plane, control plane, and cognitive plane applications. In such applications, both primary services and secondary services are participating nodes. The primary services post their merchandise on the IP backbone for sale, and the secondary services place their orders from the client hosts at the IP backbone edge. An overlay network is built on top of the node hosts, which acts as a virtual network for node control evaluation and dissemination. For shortening the data-search process and reducing routing complexity, adopting a structured P2P overlay is preferred such as DHT instead of unstructured P2P systems.

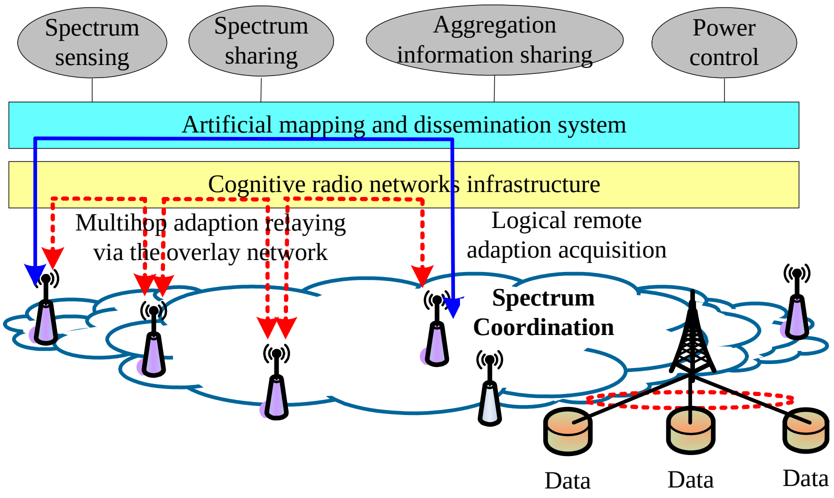

Fig. 1. Node control aggregation with artificial mapping.

In the node control aggregation environment, link state aggregation does not use external spectrum authorities to mediate link state flows. Each cognitive node can serve as a receiver or a sender and accounts for an information source. With consumer product exchanges, this is referred to as the spectrum trading mechanism which involves spectrum selling and buying processes. Clearly, benefiting from recent advancements in cognitive radio networks architectures, some P2P activities occur at the sender level. Thus a sender would always need to receive and process updates from other converged wireless nodes.

Because many dynamic factors are involved, control is difficult to quantify. As for a fully distributed P2P system concerning numerous nodes, a wireless node often can not assess another wireless node's control state efficiently, but rather have to depend on collective opinions from other nodes. Nevertheless, this brings about new challenges, considering how to identify the accuracy of the collected opinions and how to aggregate the conflicting opinions to get a *global control*. Actually, when high accuracy or updated control is desired, the global control aggregation process may be very time consuming and involves a heavy messaging overhead.

An effective P2P control system can not only addresses control locally, but aggregates the meta-control globally as well. It must accurately capture and track various local parameters, for example, secondary services should be able to capture potential primary services' credit records, or preferences in light of the goods being sold. The control plane allows cognitive radio nodes to initialize and dynamically adapt the PHY, MAC and network level parameters.

3.2 The Link State Aggregation Problem

In this section, the link state aggregation problem is formulated in CRN. The recursive computations are defined on global convergence vectors in successive aggregation cycles. Then the FuzzyConvergence system architecture is introduced and the functional modules of FuzzyConvergence are illustrated on each node. This architectural model paves the way to specify the convergence protocols for artificial mapping tree operations later. Table 1 lists all notations in this paper, and these terms will be defined with more details in subsequent sections.

Table 1. Notations and Definitions of Basic Terms.

Notation	Basic Definition
r_{ij}	the local convergence issued by node *i* for node *j*
s_{ij}	the normalized local score
$v_i(t)$	the global control score of node *i* at aggregation cycle *t*
$V(t) = \{vi(t)\}$	Global control vector over *n* peers
δ	Aggregation error threshold
C_i	the global control of node *i*
S	the set of nodes where node *i* has conducted link states,
c_{ji}	the local convergence of node *i* rated by node *j*
k	the link state step
w_j	the aggregation weight of t_{ji}
$x_i(k)$	the aggregated global score of node *i* up to step *k*
$w_i(k)$	the aggregation weight applied by node *i* at step *k*
(Min_{col}, Min_{row}), (Min_{col}, Min_{row})	the rectangular region
D	the distance between 802.16a BS and 802.11b AP

In a CRN of *n* nodes, each node evaluates the link states of other nodes with local convergence scores after conducting a spectrum transaction, such as a spectrum allocating. Consider a *convergence matrix* $R=(r_{ij})$, $1 \le i$, $j \le n$, where r_{ij} is the local convergence issued by node *i* for node *j*. If there is no feedback between two nodes, r_{ij} is set to be zero.

For global control aggregation, each node must normalize all local scores issued by itself. The *normalized local score* s_{ij} is defined as follows:

$$s_{ij} = r_{ij} \Big/ \sum\nolimits_j r_{ij} \,, \tag{1}$$

Then we have a normalized convergence matrix $S=(s_{ij})$. Note that $0 \le s_{ij} \le 1$ and each row sum $\sum\nolimits_{j=1}^{n} s_{ij} = 1$ for all rows *i*=1, 2,…, *n*. In other words, the normalized convergence matrix *S* is a stochastic matrix, in which all entries are fractions and all row entries add to be 1.

It is possible to encounter sparse trust matrix. After sufficient number of aggregations, the entries of a convergence matrix may even become all zero.

Let $v_i(t)$ be the *global control score* of node *i* at *aggregation cycle t*, where *i*=1, 2,…, *n* and *t*=0, 1, 2,…, *d* for *d* cycles. The global scores of all nodes form a *normalized convergence vector* with *n* components $V(t)=\{v_i(t)\}^T$, where $\sum\nolimits_i v_i(t) = 1$.

The iterative method specified below calculates the $V(t)$ at cycle *t*. Let $V(0)$ be the initial convergence vector value. For all iterative cycles *t* =1, 2,…, *d*, we generate successive convergence vectors, recursively, by performing the following matrix-vector computations:

$$V(t+1)=S^T \times V(t) \tag{2}$$

Initially, all nodes are equally aggregated, *i.e.* $v_i(0)=1/n$, where *i*=1, 2, …, *n*. The iterative computation continues until the average relative error between $V(d)$ and $V(d+1)$ is lower than δ for a given *aggregation error threshold* δ at the last cycle *d*.

It is showed in [14] that $d \le \lceil \log_b \delta \rceil$ with $b = \lambda_2 / \lambda_1$, where λ_1 and λ_2 are the largest and second largest Eigenvalues of the trust matrix *S*. The convergence threshold δ is predefined by system designers. After *d* cycles, the global reputation vector converges to the eigenvector of trust matrix *S*.

This recursive process is motivated by Markov random walk among nodes, which is widely used in ranking web pages. Consider a random surfer hopping from nodes to nodes to search for a convergence node. At each surfing step, the surfer selects a neighbor with regard to current distribution of local scores. The Markov chain distribution is the converged global reputation vector.

DHT-Based overlay implementation has developed scalable algorithms to calculate the global reputation vector $V(t)$ for DHT-based CRN. In this paper, we propose a FuzzyConvergence system for global control aggregation in unstructured CRN.

3.3. FuzzyConvergence System for Inference

After analyzing the characteristics of link state aggregation data, the FuzzyConvergence prototype system is built for evaluating node control in link states, and it is developed with the fuzzy logic inference technique. Specifically, the system could handle imprecise or uncertain information collected from the wireless nodes. Adopting link state aggregation characteristics, three important design criteria are suggested:

- To begin with, the network bandwidth consumption required to exchange local convergence for hot spots could be extremely high. Thus, a control plane for link states is capable of considering the unbalanced link states among users.
- Secondly, for lesser impact from small users, a control plane should not apply the same evaluation cycle for all nodes. The super users can be updated more often than the small users.
- Finally, given a skewed link state number, it makes sense to evaluate the large link states more often than the small ones.

Fig. 2 and Fig. 3 illustrate system works by performing two major inference steps: *Local Convergence Calculation* and *Global Control Aggregation*. Fig. 2 shows the local convergence calculation for link states. In *Local Convergence Calculation*, nodes perform fuzzy inference on local parameters to get the local convergence. The fuzzy inference mechanism can catch uncertainties information and is self-adjusting. Adaptively, it can track the variation of local parameters, such as interference power, interference power, bandwidth of a frequency band, path loss index, and so on.

As illustrated in Fig. 3, in *Global Control Aggregation*, the FuzzyConvergence system aggregates local convergence collected from all nodes to generate a global control for each node. The system adopts fuzzy inference to get the global control aggregation weights. The aggregation weights are identified using three variables: the node’s control, the link state aggregation date, and the link states amount. In a full-scale P2P control plane, the number of fuzzy inference rules should be extended to several hundreds. Also, Table 2 lists some frequently used fuzzy inference rules to FuzzyConvergence system construction.

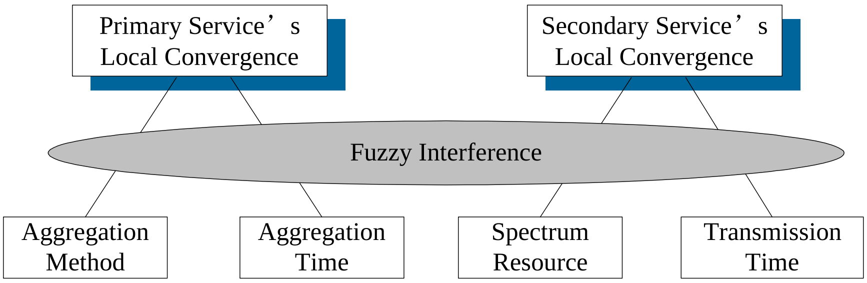

Fig. 2. Local convergence inference to determine the local convergence.

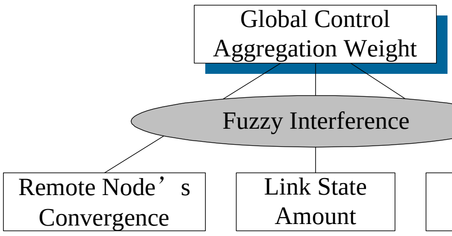

Fig. 3. Global control aggregation for weight inference.

Table 2. Fuzzy inference rules for convergence.

condition	rules
the node’s control is good and the link state amount is high	the aggregation weight is very large
the node’s control is good and the link state amount is low	the aggregation weight is medium
the node’s control is bad	the aggregation weight is very small
the link state amount is very high and the link state time is new	the aggregation weight is very large
the link state amount is very low or the link state time is very old	the aggregation weight is small

The global control is calculated in terms of the following formula:

$$C_i = \sum_{j \in S} \left(\frac{w_j}{\sum_{j \in S} w_j} c_{ji} \right) = \frac{\sum_{j \in S} w_j c_{ji}}{\sum_{j \in S} w_j}, \qquad (3)$$

where C_i stands for the global control of node i, S means the set of nodes where node i has conducted link states, c_{ji} is the local convergence of node i rated by node j, and w_j is the aggregation weight of t_{ji}. The global aggregation process performs multiple iterations until each C_i converges to a stable global control rating for node i.

The prototype FuzzyConvergence system is implemented on a DHT-based P2P overlay network, with architecture similar to that of Chord [15], a DHT ring which provides fast convergence and message transmission. The Chord system is highly scalable, robust to failure, and self-organizing in that it handles node join and leave from the system. With the DHT-based FuzzyConvergence system architecture, the overlay network is built to support the local convergence dissemination and global control aggregation.

Each node has two tables: a *link state record table* to maintain link state records with remote nodes, and a *local convergence table* to maintain remote nodes’ evaluated convergence. In terms of the link state records, the global aggregation weights are inferred through the fuzzy inference system. When performing global control aggregation, each node queries the convergence from remote nodes. To deal with the spectrum hot-spot issue, the system partially queries qualified nodes that meet an aggregation threshold.

4. Link State Aggregation Protocol with Artificial Mapping

4.1. The Link State Aggregation Protocol

The index k indicates the link state step. According to K. Hwang, et al [16], k is upper bounded by a final step g=O($\log_2 n$). The time index t refers a discrete time instance of the aggregation cycle. The upper bound for t is d iterations.

Associated with each node i is the *aggregation pair* $\{x_i(k), w_i(k)\}$ at step k. The $x_i(k)$ is the *aggregated global score* of node i up to step k. The $w_i(k)$ is the *aggregation weight* applied by node i at step k. The ratio $x_i(k)/w_i(k)$ restores the global control of node i *aggregated* up to step k.

During each link state step, each node i executes two communicating threads: One thread sends a halved aggregation pair $\{x_i(k)/2, x_i(k)/2\}$ to itself (node i) and to a randomly selected node. Another thread receives all halved pairs from other nodes and communicates the updated pair $\{x_i(k+1), w_i(k+1)\}$ as follows, where the index j covers all source nodes that have sent an aggregation pair to node i at step k:

$$x_i(k+1) = \sum_j x_j(k)/2, \quad (4)$$

$$w_i(k+1) = \sum_j w_j(k)/2, \quad (5)$$

This process continues until a *consensus score* value $x_i(k)/w_i(k)$ is reached agree on all nodes i=1, 2,…, n. The *global control* $v_j(t+1)$ for node i is thus generated on all n nodes at the final aggregation step k=g.

$$v_i(g)=x_i(g)/w_i(g), \quad (6)$$

4.2. Artificial Mapping Tree Operations

The main challenge was to address FuzzyConvergence for range-based queries *without modifying the underlying DHT*. Artificial Mapping Tree (AMT) is proposed as a distributed data structure, which can be implemented on top of a generic DHT. A simple AMT can perform single-dimensional range queries and an extension using linearization techniques, and allows us to perform multi-dimensional queries. Consequently, several operations needed to build and query this data structure using a DHT are concentrated on.

4.2.1. Lookup

As a primitive, lookup is used to perform the other AMT operations. As for a node number i, it returns the unique leaf node *leaf*(i) whose label is a prefix of i. A lookup can be developed effectively by performing a binary search with the w+1 possible prefixes concerning a w-bit key. An important feature of this lookup is that unlike traditional tree lookups, it does not require each operation to originate at the root, thus reducing the load on the root as well as nodes close to the root. Instead of a full-length node number i, minor modifications to this operation could be used to perform a lookup of a prefix j.

Binary search needs $\lfloor \log(w+1) \rfloor + 1 \approx \log w$ DHT gets, which is doubly logarithmic in the size of the data domain being indexed. It ensures that the lookup operation is extremely efficient. Nevertheless, binary search has the disadvantage that it can fail as a result of the failure of an internal AMT node. The search may not be willing to distinguish between a failed internal node, where case search could proceed downwards, and the absence of an AMT node, where case the search could proceed upwards. In this case, the AMT receiver can either restart the binary search in the hope that a refresh operation has repaired the data structure, or perform parallel gets of all prefixes of the node number i. The parallel search is guaranteed to succeed as long as the leaf node is alive and the DHT can route to it. It indicates two alternative modes of operation, low-overhead lookups using binary search and low-latency fail-over lookups using parallel search.

4.2.2 Range Query

When it comes to a one-dimensional AMT, for two node numbers m and $n (m \le n)$, a range query returns node number i contained in the AMT satisfying $m \le i \le n$. Such a range query could be performed by locating the AMT node corresponding to the longest common prefix of m and n and then performing a parallel traversal of its subtree to retrieve all the desired items.

As for multi-dimensional range queries such as those required for FuzzyConvergence, a query for all matching data within a rectangular region defined by (Min_{col}, Min_{row}) and (Min_{col}, Min_{row}) is performed as follows. This linearized prefix which minimally encompasses the entire query region is identified. It is done by computing the z-curve node numbers Min_z and Max_z for the two end-nodes of the query, and the longest common prefix of these node numbers: *zPrefix*. Then the AMT node is looked up involving *zPrefix*, and run a parallel traversal of its subtree. In contrast with the simpler situation of one-dimensional queries, not all nodes between the leaf nodes for the minimum node number and the leaf nodes for the maximum node number account for the query result.

Clearly, the query process runs as follows: To start with the AMT node corresponding to *zPrefix*, whether this node is a leaf node is determined. If so, the range query is applied to all items within the node and report the result. If the node is an interior node, its left subtree, with a prefix of *zPrefix*+“0”, can promote the results to the query. It is done by identifying whether there is any overlap in the rectangular region defined by the subtree prefix and the range of the original query. The check can be implemented with no additional gets, so involves almost no penalty if it fails. If an overlap exists, the query is propagated down the left subtree recursively. Similarly, a similar test for the right subtree is implemented, with a prefix of *zPrefix*+“1”, and if the test succeeds, it propagates the query down that sub-tree as well. So the query operation needs no more than the depth of the tree’s sequential steps.

4.2.3. Insert and Delete

Insertion and deletion of a node number *i* need a AMT lookup to first locate the leaf node *leaf*(*i*). During insertion, if the leaf node is already full to its limit of w_j values, it has to be split into two children. In most situations, the (w_j +1) keys are distributed among the two children such that each of them stores at most w_j. It is clear that all (w_j +1) keys will be distributed to the same child, thereby necessitating a further split. For avoiding this case, the split operation identifies the longest common prefix of all of the (w_j +1) keys and creates two new leaf nodes one level deeper than that common prefix, thus making that neither of the new leaf nodes has more than w_j keys. These keys are distributed across these two new leaf nodes and all nodes in between the original node being split and the new leaves are marked as interior nodes. These operations could be parallelized for efficiency. Simultaneously, when a key is deleted from the AMT, it could be possible to coalesce two sibling leaf nodes into a single parent node. This merge operation is essentially the reverse of splits and can be performed lazily in the background.

5. Experimental Results

5.1. Simulation Parameters

A simulation scenario is implemented to deal with how parameter, policy and convergence operations influence the efficacy of systems in terms of QualNet [17]. Dynamically, the platform updates the communication infrastructure by manipulating its heterogeneous constituent network elements, where wireless nodes are assumed to have a wide range of characteristics, concerning mobility costs and available transmission power. It continuously seeks to fulfill concrete end-to-end QoS requirements for a set of application level multi-hop connections between end node pairs. By leveraging cooperative mobility, the platform achieves this: it investigates new locations for cooperative battlefield MANET nodes, while adhering to its mobility budget constraints. In this exposition, QoS requirements are stated in accordance with maximum acceptable end-to-end connection bit error rates (BER), but it is noted that the platform could seamlessly integrate arbitrary and richer QoS definitions. Fig. 4 shows a modular schematic diagram of this platform, and it is developed as a modular discrete event simulator which is naturally organized in layers.

In this co-existing scenario, IEEE 802.16a and 802.11b networks and the convergence schemes for artificial mapping were designed and simulated. The interference model is in accordance with the calculation of SINR

$$SINR_i = \frac{\text{RxPower of device}\,i}{\text{Noise} + \sum_{\text{Overlap Proportion}} \text{InterferencePower}}, \quad (7)$$

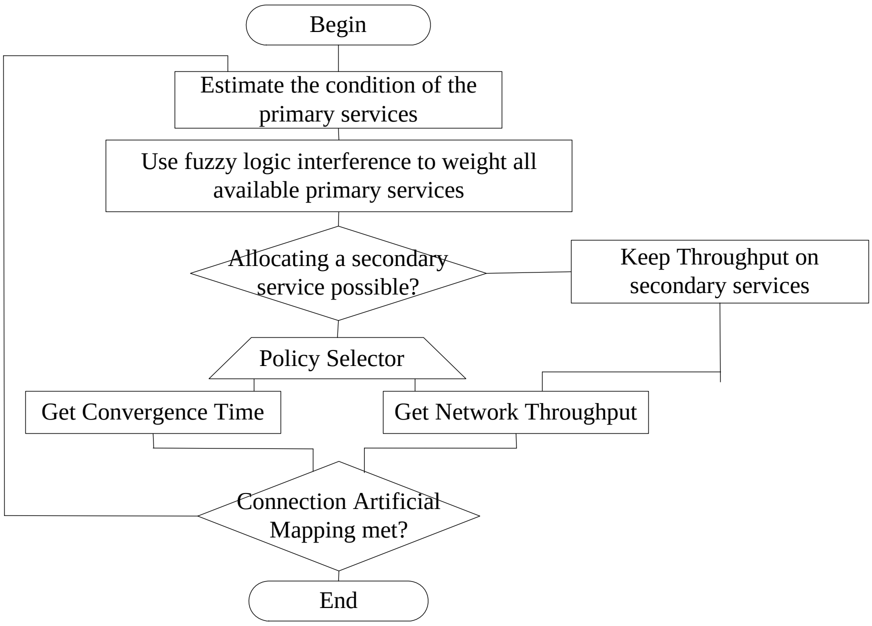

Fig. 4. Primary service selection process.

where the interference power (in watts) is summed over overlapped regions (in frequency and time) of transmitted signals (OFDM and DSSS). Bit Error Rate (BER) can be obtained by looking up the modulation performance curve with knowledge of SINR. We simulated the artificial mapping of IEEE 802.16a and IEEE802.11b for DHT-based overlay with AWGN and two ray ground propagation models. For each case, the background nose density is -174 dBm/Hz and receiver noise is 9dB. The MAC protocol for IEEE 802.16a is TDMA with 3 non-overlapping frequency bands, while the MAC protocol for IEEE 802.11b is BSS mode with 11overlapping channels. The receiver sensitivity follows -80 dBm for IEEE 802.16a and -80 dBm IEEE 802.11b. The simulation calculates local convergence inference and global control aggregation.

5.2. Simulation Results

5.2.1. Effect of Artificial Mapping for Spectrum Overlapping

Artificial mapping for spectrum overlapping methods are first evaluated in a simple network scenario with one 802.11b hotspot (1 AP in the center and several clients) and one 802.16a cell (one BS and one SS). In this simulation, the distance *D* between 802.16a BS and 802.11b AP is a varying parameter and the hotspot radius is fixed at 100 meters. The 802.16a cell will always operate on 802.16a frequency band index centered at 2412 MHz, which will totally overlap with 802.11b hotspot if it operates on band 1. But if 802.11b devices change to band 2, 3, or 4, the two systems only have partial overlapping bands. With artificial mapping, 802.11b devices are able to avoid interference with 802.16a by switching their operating frequency bands dynamically. The power adjustment is the transmit power adjustment controlled by transmitter power constraints, which is not considered currently.

In Figs. 5 and 6, as switching to different frequency bands, as both systems have overloaded CBR traffic, the *x* axis is the 802.11b frequency band number index 1 to 3. *x*=4 corresponds to the situation without 802.16a traffic, *i.e.* no interference, and the *y* axis is the number of transmission pairs in one hotspot, ranging from 1 to 6 pairs. As is shown in Fig. 5, the hotspot is near the 802.16a BS, these systems degrade since interference is strong. When *D*=1.5 km, there is still interference because of complete overlap at frequency band index 1 and 5. Nevertheless, for frequency band indices greater than 3, the link throughput is almost unaffected by interferer nodes. For partial overlap at frequency band 2, the throughput is still degraded. The advantage of avoiding interference by switching 802.11b frequency bands to other available bands is observed in this case.

The dynamic resource management is designed, where the control radio uses 802.11b operating at fixed frequency band 1 with 2 Mbps rate covering about 250 *m*. The control MAC uses the IEEE 802.11 standard without RTS/CTS. The data radio can be achieved with generic radios, but without loss of generality, 802.11a OFDM radio parameters at 5 GHz is utilized for *Cognitive Plane* with 8 frequency bands of 20 MHz each. The scenario is composed of varying numbers of wireless nodes in a 1 km × 1 km of unit area, where nodes are randomly placed in the CRN and boot up at random times. In terms of network setup time, control overhead used and estimated achievable end-to-end rate, the convergence validation with spectrum coordination is discussed. The maximum network setup time is the time from the start of the first node to the time all nodes in the CRN achieve global awareness by completing the reconfiguration process. To evaluate the protocol, different traffic source and destination pairs are selected randomly to manipulate data ON/OFF sessions.

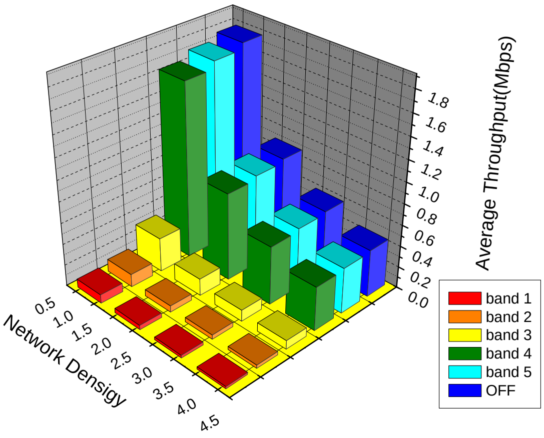

Fig. 5. Average link throughput with *D*=1 km.

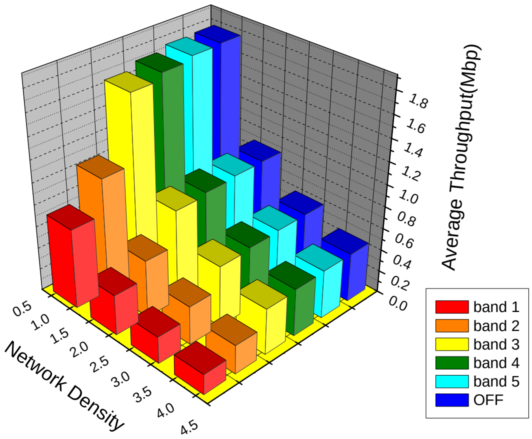

Fig. 6. Average link throughput with *D*=1.5 km.

5.2.2. Convergence Validation Result

The simulation results are compared for cases where all reconfiguration states are sent periodically (convergence all), or alternatively only when changes occur (convergence changes). Fig. 7 and 8 show the maximum and average network convergence time, in which nodes randomly boot up from 0 to 2 s. With increasing number of nodes in the network, the network setup time first decreases and then increases, reaching its minimum at a node density. As the network is sparse, more convergence steps are required to discover the whole network, and it takes about 3~8 iteration steps to discover the network in a very dense network. Note that when only changed reconfiguration states are propagated, the network converges faster due to reduced control packets contending for the control bands.

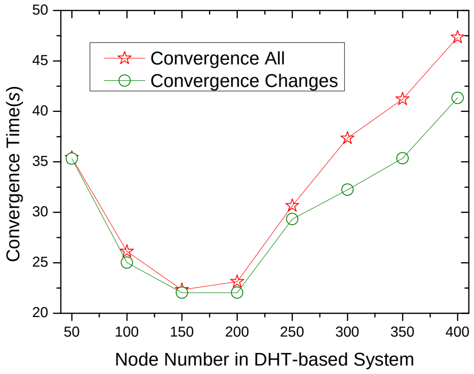

Fig. 7. Maximum network convergence time.

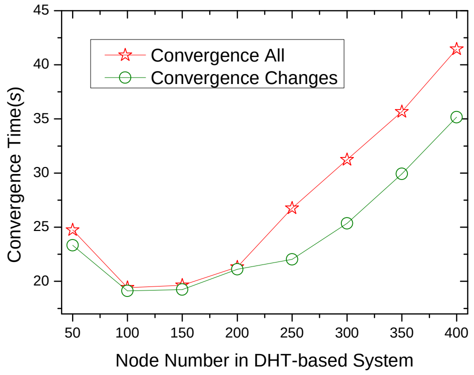

Fig. 8. Average Network convergence time.

5.2.3. Throughput for Uniformly Distributed and for Clustering Distributed

Apart from the above network scenario, four 802.11b hotspots with 4 clients and 1 AP per hotspot are placed in one 802.16a cell with 1 km away from the BS. 802.11b nodes are randomly placed inside the hotspot with the distance to AP. The following geographic distributions of 802.16a SS were addressed: (a) randomly uniformly distributed inside the 802.16a cell with a radius of 1.5 km, and (b) clustered around each hotspot with the distance to each AP. The larger the clustering index, the more closely the cluster couples spatially with hotspots, and thus the higher the interference between the two systems. The total number of 802.16a SS is kept the same as the total number of 802.11b clients in the CRN and the traffic type is the same as the previous simulation.

As for the distribution in Figs. 9 and 10, the results for convergence in frequency denoted are compared with common spectrum coordination with CSCC [18]. Both 802.16a DL and UL traffics are considered. Fig. 9 shows the situation with randomly-distributed 802.16a SS. There are 802.16a SS nodes with 12 nodes in each 802.16a channel, when Pareto traffic with ON/OFF time=500 ms/500 ms. Fig. 10 shows the situation with clustering-distributed SS nodes. The results show the case with convergence can significantly improve the average network throughput, up to about 67% in randomly distributed case and about 130% in the clustering case. It also performs better than CSCC when the 802.16a SS node density is not very high, which means there is vacant spectrum for the two systems to operate in different frequency bands.

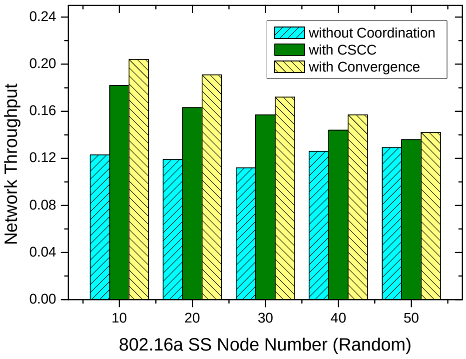

Fig. 9. Throughput for uniformly distributed.

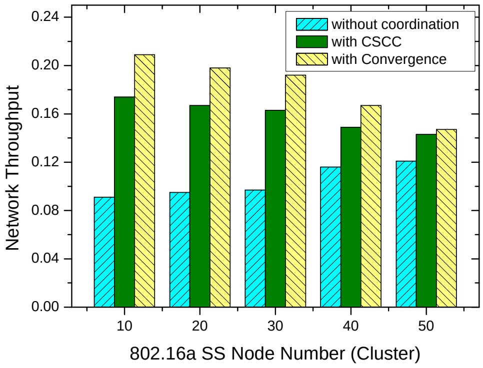

Fig. 10. Throughput for clustering distributed.

6. Conclusions

The resource management for the future heterogeneous network is demonstrated in this paper. To meet the future cognitive radio networks convergence, the artificial mapping approach is proposed. The design considerations are thoroughly discussed. The analysis indicates that the fuzzy logic interference could be a clearly effective for distributed management in heterogeneous wireless environment. A FuzzyConvergence system is designed as a mechanism to enable efficient spectrum etiquettes, and it is shown that it enables each node to dynamically decide on an affordable message overhead in terms of local information. Also, with the performance advantages in dense or clustered networks environment, the DHT-based overlay is implemented. Based on the Artificial Mapping Tree (AMT), the multi-dimensional range queries can exert various operations needed to build and query data adaptively.

The experiment results verify the analysis. By artificial mapping, wireless devices are capable of avoiding interference with others by switching their operating frequency bands dynamically. Further, the benefit of global control aggregation is observed in this case. Compared with today’s adaptive network collaboration approach, the artificial mapping approach is very promising from the standpoints of both performance and convergence effectiveness.

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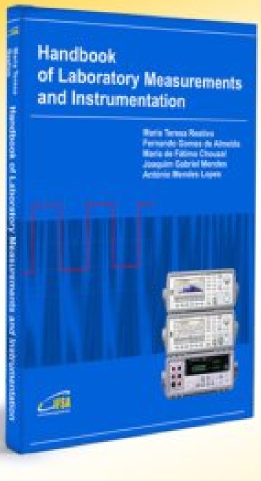

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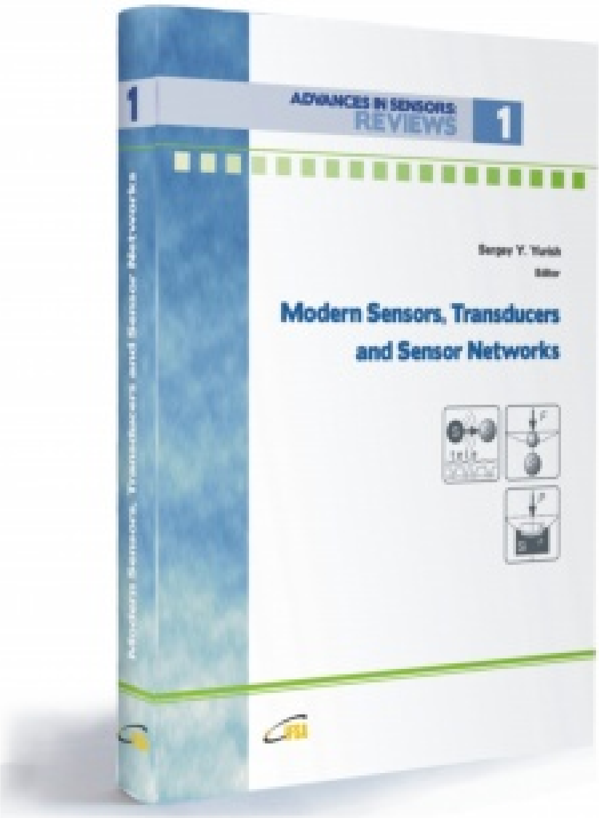

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