Consensus-Based Cognitive Radio Assisted Cooperative Communications

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ABSTRACT
This paper develops a framework for cooperative communications between multiple clusters of nodes connected in ad hoc fashion. The intermediate clusters are used to cooperatively relay the information from nodes in source cluster to the nodes in destination clusters. Since the nodes in relay clusters use the wireless resources as primary users, the relay clusters are Cognitive Radio (CR) enabled to make efficient use of idle resources by sensing, reporting and sharing cognitive parameters without any service interruption in relay clusters. We also developed a consensus-based power management scheme to adjust and maintain the transmit power and consequently the bitrate in relay clusters at an acceptable level to make sure that there are always connecting paths for delivering the packets. We demonstrate the performance improvement in terms of outage probability and end-to-end Symbol Error Rate (SER) and Blocking Rate for M-QAM modulation in Rayleigh fading environment with AWGN.

Categories and Subject Descriptors
C.3 Special-purpose and Application-based Systems: Signal processing systems

General Terms
Design

Keywords
Cooperative, Consensus, Cognitive Radio, Cluster, Relay, Primary Users, Secondary Users.

1. INTRODUCTION
The *cooperative communications* seems to be a necessary aspect in future communication systems in both infrastructure and non-infrastructure i.e. *Ad Hoc* networks. This implies that the mobile nodes need to interact with each other in order to deliver the service. Recent researches show that there is a great potential of increasing system capacity, coverage and reliability as well as quality of service by taking advantage of cooperative multiplexing and diversity [14].

There are various implementations of cooperation like routing, relaying and more recently network coding. The nodes are distributed uniformly in clusters and cooperation takes place in both intra-cluster and inter-cluster fashion. In this paper, we consider a scenario where some nodes tend to communicate with other nodes in a distant cluster and there are some clusters in between. In the prior works on cooperative communications, there is no mechanism to manage the resources in order to best accommodate both cooperating nodes and secondary users from source clusters. Some sub-channels are actively used by the users in intermediate clusters i.e. relay clusters while some portions of wireless resources remain idle. The originating nodes in source clusters can use these idle resources and become secondary users for primary users in relay clusters. In this paper, we introduce The Cognitive Radio as a means to improve the utilization of wireless spectrum resources and increase the probability of existence of a connecting path between source and destination clusters. The packets are delivered through cooperating nodes in relay clusters via multiple hops by evaluating the quality of the links. The task of maintaining the wireless links at a satisfactory level of availability and reliability is addressed in this paper and resolved by a consensus-based power management method. The consensus-based power management mechanism adaptively adjusts the transmit power in all neighborhoods and ultimately in all across the network without having access to global information about the network. This will reduce the power consumption as well as the total interference level in relaying clusters. This method can be used in improving the overall cooperative behavior and ultimate performance of the network. We calculate the end-to-end SER and the outage probability for cooperative communications and demonstrate how consensus-based power management improves the performance.

2. SYSTEM MODEL
We consider a multi-cluster system of ad hoc networks to introduce our cooperative model consisting of source, relay and destination clusters. Each cluster is a graph with topology G(V, E) where $V = \{u_1, u_2, \dots, u_N\}$ denotes the cluster vertices and $E = \{e_{ij} : (v_i, v_j) \in V\}$ is the unconstraint set of all edges on graph G. Each cluster is distinguished from its neighbors by defining a connection criterion. For a group of nodes spatially distributed in an area of a certain radius, the channel capacity for the link between any given pair (i,j) of nodes over a channel of bandwidth W_{ij} is defined as:

$$C_{ij} = W_{ij} Log_2(1 + SINR_{ij}) \qquad (1)$$

The set $E=\left\{(v_i,v_j)\in V; C_{ij}\ge R_{th}=\frac{B}{T_s}\right\}$ is the cluster membership criterion. Where R_{th} is the minimum acceptable rate for a block of data B in T_S seconds.

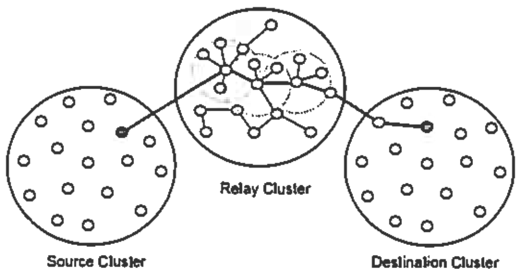

Figure 1. Three-cluster system with consensus-based cognitive clusters

When nodes in source cluster want to cooperatively send the information to destination cluster they use the relay cluster and the source nodes are considered as secondary users for the relay cluster as nodes in relay cluster are actively using the resources. Some nodes are idle and some have access to idle resources. Either way they can turn into cooperating nodes. The data packets travel through the relay cluster using several hops in which either idle resources are used or some prioritization is needed to guarantee the delivery towards destination cluster.

2.1 Basic Cooperative Communication Model

For a three-cluster system where nodes in source cluster tend to communicate with nodes in destination cluster, we can consider a three-phase communication model.

2.1.1 Phase 1: source broadcasting

In this phase, the source nodes start to broadcast with power P_s for T_S seconds and all nodes in relay cluster listen to the source nodes. For a data block B the links are evaluated using below inequality:

$$B \le W_{sr} T_S \log_2\left(1+\frac{P_s|h_{sr}|^2}{N_0}\frac{k}{d_{sr}^{\alpha}}\right) \tag{2}$$

Where $s = 1,2,\dots,N_S$, $r = 1,2,\dots,N_R$. N_S, N_R and N_D are the number of nodes in source, relay and destination clusters respectively. d_{sr} is the distance between the source and relay nodes. α is determined based on the path loss model as $2 \le \alpha \le 4$. h_{sr} is the channel between nose s and node r. Only those relays that can meet (2) participate in relay selection and the rest do not bother to contend as this wastes the energy and introduces interference without improving the throughput.

2.1.1 Phase 2: Relay selection phase

In this phase, the relays contend for T_R seconds and the best relay is selected using a global set of information.

2.1.2 Phase 3: Data Delivery Phase:

The same evaluation process is repeated to deliver the block of data to destination.

$$B \le W_{rd} T_R \log_2\left(1+\frac{P_r|h_{rd}|^2}{N_0}\frac{k}{d_{rd}^{\alpha}}\right) \tag{3}$$

Where $d = 1,2,\dots,N_D$. The data block is transmitted only if (3) is met.

3. CONSENSUS-BASED COGNITIVE-ASSISTED MODEL

In our new model, CR enabled nodes in relay clusters measure and report the list of cognitive parameters like idle resources, link suitability metric, QoS, probability of presence and etc. Let $C^R(n)=\left\{c^R_{jm}(n)\right\}$ be the link suitability matrix for relay cluster at time $t = nT_R$ where c^R_{jm} is the link metric for every node j in relay cluster and its neighbor node m in set Δ_j. The set Δ_j represents the node j neighbors. Index l, j and k are used for nodes in source, relay and destination cluster respectively.

$$C^R(n) = \left[c^R_{jm}(n) = \frac{|h_{jm}(n)|^2}{d^{\alpha}_{jm}(n)} - \gamma_j\right] \tag{4}$$

Where $m = 1,2,\dots,N_R$ and $j = 1,2,\dots,N_R$. For any neighborhood the common terms are:

$$\gamma_j = \left(2^{\frac{B}{W_{jm}T_S}} - 1\right)\frac{N_0}{KP_j} \tag{5}$$

This metric can be reported to node j neighbors and node j neighbors report theirs to node j so that all nodes have this information about their neighbors. For any node j, the performance information are updated periodically in every neighborhood so node l knows which links are good enough to be used for next forwarding hop. One of the reasons that nodes may not forward the packets in the cooperative process is bad channel conditions which can be addressed with error correction techniques. Subsection C will introduce an adaptive technique to resolve this as well.

A node is called *malicious* if all the originating and terminating links to it cannot meet the minimum bitrate i.e. its corresponding row (column) in C^R is all non-positive numbers.

$$V_{mal} = \left\{v_j \in G^R; c^R_{jm}(n) \le 0, v_m \in \Delta_j\right\} \tag{6}$$

Malicious nodes do not participate in cooperation until they meet the minimum bitrate requirement. Here we define a *cooperative neighborhood* as a group of immediately connected nodes namely Δ_c that are able to participate in delivering the packets to the next hop.

3.1 Cognition procedure

We use the *Cognitive Radio* model discussed in [6] where $\Phi(R) = S$ and $\Psi(U) = M$ are the *Channel Indexing Function* (CIF) for idle resources and *User Merit Function* (UMF) respectively. $R = \{r_1, r_2, \dots, r_L\}$ denotes the set of available resources reported by the CR nodes in relay cluster and $S = \{s_1, s_2, \dots, s_L\}$ is the sorted resource performance indices based on carrier-to-Interference and probability of availability for each sub-channel. $M = \{m_1, m_2, \dots, m_L\}$ is the sorted set of merit values for all requesting users based on the node degree, QoS and SINR.

$$s_1 \ge s_2 \ge \dots \ge s_L \qquad m_1 \ge m_2 \ge \dots \ge m_L \tag{7}$$

[6] Applies the *rearrangement inequality* to generate a selection criterion in allocating the idle resources to requesting nodes:

$$T_{opt} = \sum_{i=1}^{L} s_i m_i \ge \sum_{i=1}^{L} \sigma_p^{(L)}(s_i)\sigma_q^{(L)}(m_i) = T_{rand} \tag{8}$$

Where $\sigma^{(L)}$ denotes any cyclic random permutation with cycle L operating on its input. The best possible idle channels in relay cluster will then be assigned for relaying the packets from source to destination. These idle resources are assigned to jth node in relay cluster with best link suitability metric.

3.2 Proposed Cooperative Algorithm

- Node i in source cluster broadcasts
- All nodes in relay cluster listen to node i
- Every node in relay cluster has an updated copy of the relay table
- The cooperating node j is the one that can deliver the packet to the next hop meaning that there are qualified paths between node i in source cluster and node j in relay cluster and node k in destination cluster.

Let $C^{SR}(n)$ be the link suitability matrix between source and relay clusters.

$$C^{SR}(n) = \left[c_{ij}^{SR}(n) = \frac{|h_{i,j}(n)|^2}{d_{i,j}^{n}(n)} - \gamma_i\right] \tag{9}$$

Every node j in relay cluster listens to the broadcasts received from nodes in source cluster. Then it picks the one that has a strongest metric.

3.3 Power management through consensus

To guarantee the minimum bit rate for links in relay cluster and existence of a connecting path between source and destination, we propose an adaptive mechanism based on a consensus protocol. The *Consensus Protocol* is an interaction rule that specifies the information exchange between an agent and all of its neighbors in the network leading to update the agents' properties. We distribute the power management task across the cluster and localize the decision making process down to neighborhoods.

$$P_j(n+1) = P_j(n) + \frac{1}{|\Delta_j|+1}\sum_{v_m\in\Delta_j} a_{jm}^{R}\left[P_m(n) - \left(2^{\frac{R}{W_{jm}T_n}} - 1\right)\frac{N_m P_{jn}(n)}{K|h_{jm}(n)|^2}\right] \tag{10}$$

$A^R = \{a_{jm}^R\}$ is the topology adjacency matrix of relay cluster. Every node j has the information about the links to its neighbors. The matrix representation for all nodes in relay cluster will then be:

$$P(n+1) = \Pi P(n) \tag{11}$$

Where $\Pi = I + (I + D)^{-1}A'$ and A' is the modified adjacency matrix whose entries $\{a'^{R}_{jm}\}$are adjustment transmit power for link (j, m).The consensus-based power management adaptively adjusts the transmit power in all neighborhoods and ultimately in all across the network without having access to global information about the network. The steady state transmit power is given in [1].

$$P_{ss} = \Omega\Sigma^{T}P(0) \tag{12}$$

Where Σ and Ω are the left and right eigenvectors of Π respectively.

3.4 Increased cooperation reliability

The protocol selects two highest metrics and uses them as (1+1) protection for the relay link but this has to be matched against the output of the CR function to make sure that the selected links can use the available resources.

4. COOPERATIVE TRANSMISSION PERFORMANCE

In this section, we first study the SNR probability function and then develop the end-to-end PDF of SNR in order to obtain the SER for M-QAM modulation.

4.1 PDF of SNR for a single hop cooperative transmission

For a single hop link between nodes i and j, with Rayleigh fading channel h_{ij}, the received signal has a PDF as:

$$p(r) = \frac{r}{\sigma_n^2}e^{\frac{-r^2}{2\sigma_n^2}} \tag{13}$$

with $\sigma_n^2 = \frac{N_0}{2}$. $\gamma = \frac{r^2 T_S}{2\sigma_n^2}$ is the SNR and the average SNR of single link will be: $\bar{\gamma} = E\{\gamma\} = \frac{|h_{ij}|^2\varepsilon_s}{N_0}$. ε_s represents the symbol energy. The PDF for γ is[13]:

$$f_\gamma(\gamma) = \frac{1}{\bar{\gamma}}e^{\frac{-\gamma}{\bar{\gamma}}} \tag{14}$$

4.2 End-to-End SER for multi-hop cooperative transmission using M-QAM modulation

For a multi-hop relaying path of N hops:

$$\gamma_{eq} = \min_{j=1,2,\ldots,N} \gamma_j \tag{15}$$

Where γ_j is the SNR for jth hop. The CDF for γ_{eq} will be:

$$F_{eq}(\gamma) = 1 - Pr[\gamma_1 > \gamma_2 \ldots > \gamma_N > \gamma] = 1 - \prod_{j=1}^{N} \Pr_{\gamma_j}(\gamma_j > \gamma)$$

$$F_{eq}(\gamma) = 1 - \prod_{j=1}^{N}\left[1 - F_{\gamma_j}(\gamma)\right] \tag{16}$$

By differentiating the CDF we get the PDF as:

$$f_{\gamma_{eq}} = \sum_{j=1}^{N} f_{\gamma_j}(\gamma)\prod_{\substack{i=1\\ i\neq j}}\left[1 - F_{\gamma_j}(\gamma)\right] \tag{17}$$

$$f_{\gamma_{eq}}(\gamma) = \sum_{j=1}^{N}\frac{1}{\bar{\gamma}_j}exp(\frac{-\gamma}{\bar{\gamma}_j})\prod_{\substack{i=1\\ i\neq j}}^{N}\left[1 - 1 - exp(\frac{-\gamma}{\bar{\gamma}_j})\right] = \sum_{j=1}^{N}\frac{1}{\bar{\gamma}_j}exp(-\gamma\sum_{j=1}^{N}\frac{1}{\bar{\gamma}_j})$$

Let $\beta = \sum_{j=1}^{N}\frac{1}{\bar{\gamma}_j}$ then:

$$f_{\gamma_{eq}}(\gamma) = \beta exp(-\beta\gamma) \tag{18}$$

Where γ_s is the SNR per symbol. where $g = \sin^2(\frac{\pi}{M})$. for MQAM modulation the symbol error probability will be[13]:

$$P_s(\gamma_s) = \frac{4}{M}(1 - \frac{1}{\sqrt{M}})\int_0^{\frac{\pi}{2}} \exp(\frac{-g\gamma_s}{\sin^2\phi})d\phi - \frac{4}{M}(1 - \frac{1}{\sqrt{M}})^2\int_0^{\frac{\pi}{4}} \exp(\frac{-g\gamma_s}{\sin^2\phi})d\phi \tag{19}$$

The Moment Generating Function (MGF) for Rayleigh fading will be:

$$M_{\gamma_s}(s) = E[e^{s\gamma}] = \int_0^{\infty} f_{\gamma}(\gamma)e^{s\gamma}d\gamma = (1 - s\bar{\gamma}_s)^{-1} \qquad (20)$$

Where γ_s is SNR per symbol. Using MGF the average SER will be:

$$\bar{P}_s = \int_0^{\infty} P_s(\gamma_s) f_{\gamma_{eq}}(\gamma)d\gamma = \qquad (21)$$

$$\frac{4}{M}C_1\int_0^{\frac{\pi}{2}} M_{\gamma_s}\left(\frac{-g}{\sin^2\phi}\right)d\phi - \frac{4}{M}C_1^2\int_0^{\frac{\pi}{4}} M_{\gamma_s}\left(\frac{-g}{\sin^2\phi}\right)d\phi$$

Where $C_1 = (1 - \frac{1}{\sqrt{M}})$ and $C_2 = \sqrt{\frac{g\bar{\gamma}_s}{1+g\bar{\gamma}_s}}$ given that MGF for Rayleigh fading is [15]:

$$M_{\gamma_s}\left(\frac{-g}{\sin^2\phi}\right) = \left(1 + \frac{g\bar{\gamma}_s}{\sin^2\phi}\right)^{-1} \qquad (22)$$

From (21) and (22) we have:

$$\bar{P}_s = \frac{4}{M}C_1\left\{\frac{1}{2}\left[1 - C_2\frac{2}{\pi}\left[\frac{\pi}{2} + \tan^{-1}(C_2\cot^{-1}(\theta))\right]\right]\right\}$$
$$- \frac{4}{M}C_1^2\left\{\frac{1}{4}\left[1 - C_2\frac{4}{\pi}\left[\frac{\pi}{2} + \tan^{-1}(C_2\cot^{-1}(\frac{\theta}{2}))\right]\right]\right\}$$

Where $\theta = \frac{\pi}{2(M-1)}$.

4.3 Outage probability

The outage probability is defined as a probability when equivalent SNR goes below a certain threshold γ_{th}[13]:

$$P_{out} = \Pr(\gamma_{eq} < \gamma_{th}) = \int_0^{\gamma_{th}} f_{\gamma_{eq}}(\gamma)d\gamma = 1 - \exp(-\gamma_{th}\beta) \qquad (23)$$

We consider a three-cluster network consisting of multiple nodes. A uniform power allocation is employed in order to keep the total power constraints as:

$$\sum_{r=1}^{N_h} P_r = P_t \qquad (24)$$

The consensus-based power management does not shift the power constraint in (16)

$$\beta = \sum_{j=1}^{N}\frac{1}{\bar{\gamma}_j} = \frac{NN_h}{P_t} \qquad (25)$$

$$\beta' = \sum_{j=1}^{N}\frac{1}{\bar{\gamma}_j} = \frac{NN_h}{P_{ss}} \geq \frac{NN_h}{P_t} = \beta \qquad (26)$$

From (26) we see that:

$f_{eq}(\gamma) \geq f'_{\gamma_{eq}}(\gamma)$, $P_{out} \geq P'_{out}$ and $\bar{P}_s \geq \bar{P}'_s$

5. SIMULATION

We considered a three-cluster system of 100 nodes each. 84 resources are available for each cluster. The incoming request rate λ_{in} from source cluster is drawn from a Poisson distribution and CR algorithm chooses the best channels for most rightful requesting nodes [6]. Figure 2, 3 show the outage probability for different γ_{th} and modulation schemes. The performance has improved when we used power management mechanism. Figure 3 shows the SER improvement for different modulation schemes. Figure 4 shows how transmit power converges to an optimum level using consensus algorithm. Figure 5 demonstrates the *Blocking Rate* improvement using *Cognitive Radio* in relay clusters.

6. CONCLUSION

In this paper, we developed a model for cooperative communication where the relay clusters use cognitive radio to efficiently use the idle resources when needed. It turns out that adaptive power management in general and consensus-based methods in particular improve the performance as well.

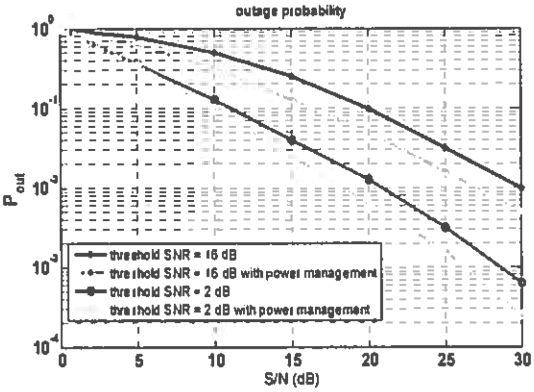

Figure 2. outage probability with and without Consensus-based power management for a three-cluster system using CR in relaying

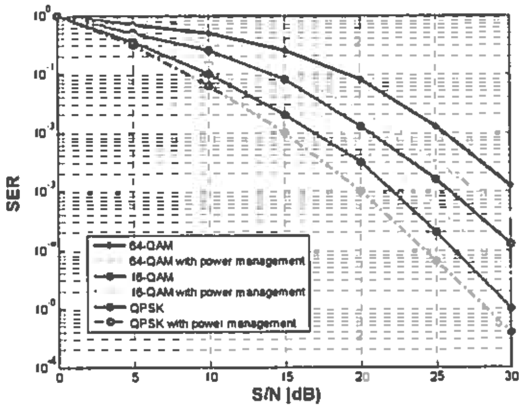

Figure 3. SER improvement using Consensus-based power management for a three-cluster system using CR in relaying

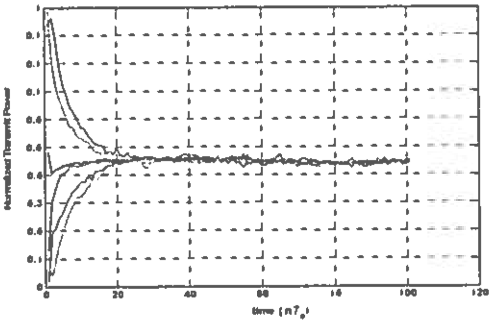

Figure 4. Transmit power adjustmen using consensus protocol for a neighborhood of 6 nodes in a cluster of 100 nodes

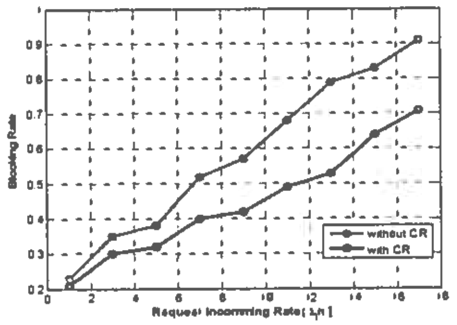

Figure 5. Blocking Rate improvement using CR in relay cluster during cooperative process

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