

# Enhanced Node-Level Cooperation of Cognitive Radio Based Ad hoc Wireless Networks Using Overlay Approach

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**Abstract**— Ad hoc Wireless Network can be deployed anywhere easily without requiring planned infrastructure. It is a decentralized network. Users are mobile in this network and can access data from anywhere. In Ad hoc wireless mode, from source node to destination node requires help of other nodes presents in the vicinity of a node. Nodes behave as a source and destination and as a router or intermediate node which forward data for other nodes. Routing becomes on the most complicated challenges prevailing in Ad hoc Wireless Networks. Routing is based on multi hop and so no default route is available. Traditional classification of Ad hoc network routing is table driven and on-demand driven protocols. Table driven routing protocols try to maintain consistent, up-to-date routing information from each node to every other node. Energy is considered as a vital resource that needs to be preserved in order to extend the life time and stability of the Ad hoc Wireless Networks. In particular, mobility changes network connectivity and it can reduce the stability of the link of nodes and it can reduce the performance of throughput. In order to overcome these issues in Ad hoc Wireless Networks, Optimization techniques are proposed. Existing spectrum sharing paradigms have set clear boundaries between the primary and secondary networks. There is either no or very limited node-level cooperation between the primary and secondary networks. In this paper, we develop a new and bold spectrum-sharing paradigm beyond the state of the art for future wireless networks. We explore network cooperation as a new dimension for spectrum sharing between the primary and secondary users. Such network cooperation can be defined as a set of policies under which different degrees of cooperation are to be achieved. The benefits of this paradigm are numerous, as they allow integrating resources from two networks. There are many possible node-level cooperation policies that one can employ under this paradigm. For the purpose of performance study, we consider a specific policy called United cooperation of Primary and Secondary (UPS) networks. UPS allows a complete cooperation between the primary and secondary networks at the node level to relay each other's traffic. As a case study, we consider a problem with the goal of supporting the rate requirement of the primary network traffic while maximizing the throughput of the secondary sessions. For this problem, we develop an optimization model and formulate a combinatorial optimization problem. We also develop an approximation solution based on a piece-wise linearization technique. Simulation results show that UPS offers significantly better throughput performance than that under the interweave paradigm.

**Keywords**—Mobile Adhoc Network (MANET), Industrial Scientific and Medical (ISM), Cognitive Radio(CR), Underlay, Overlay, Spectrum, United cooperation of Primary and Secondary (UPS)

## I. INTRODUCTION

The modern Mobile communication has witnessed rapid advance in the research and development of spectrum-sharing technologies. The sharing of 2.4 GHz of ISM Band radio spectrum with non-government entities in order to spur economic growth. This further accelerated the pace of commercialization of innovative spectrum-sharing technologies. Based on this innovative idea, our team began to realize that what was needed was a much more aggressive and broader vision for enhancing spectrum utilization. In [7], Goldsmith et al. outlined three spectrum-sharing paradigms for cognitive radios (CR), namely underlay, overlay, and interweave. These three paradigms were defined from an information theoretic perspective, solely based on how much side information (e.g., channel conditions, codebooks) is available to the CRs. In the networking community, these three paradigms have been mapped into specific scenarios of how primary and secondary networks interact with each other for data forwarding. The underlay paradigm refers to that secondary users' activities or interference on primary users is negligible (or below a given threshold). In contrast to the interweave paradigm, secondary users may be active concurrently with the primary users in the same vicinity and in the same frequency. Potential interference from the secondary users may be properly canceled (by the secondary users) via various interference cancelation (IC) techniques so that residual interference are negligible to the primary users [5], [13]. In this paper, we develop a paradigm with a much broader vision beyond the state of the art. We explore network cooperation as a new dimension for spectrum sharing between primary and secondary nodes. Such network cooperation can be defined as a set of policies under which different degrees of cooperation are to be achieved. Corresponding to each cooperation policy, a traffic-forwarding behavior for primary and secondary users can be defined.

One such primitive policy, as that in [9], [15], is to have secondary network help relay primary users' traffic. Another policy (United cooperation of Primary and Secondary (UPS) [23][28]), which we will use as a main policy example in this paper. To concretize our discussion on policy-based network sharing, we consider the UPS policy in detail, where UPS is the abbreviation of United cooperation of Primary and Secondary networks [23].

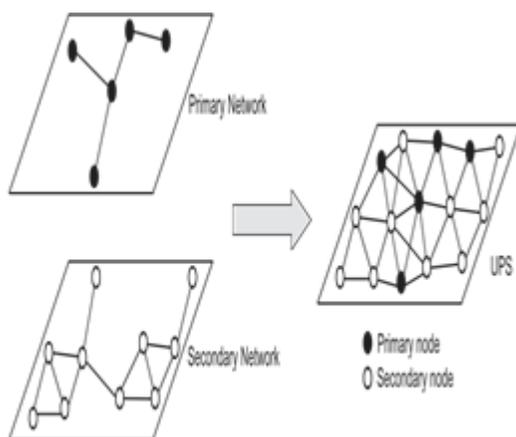


Fig. 1. Network topologies under the interweave and the UPS policy.

UPS represents a policy that allows a complete cooperation between the primary and secondary networks to relay each other's traffic. For performance evaluation, we study a problem with the goal of supporting the rate requirements of the primary sessions while maximizing the throughput of the secondary sessions. A number of technical challenges must be addressed in this problem, including how to provide guaranteed service for the primary traffic while supporting as much the secondary traffic as possible, how to select the optimal relays and routing paths for each source and destination pair, and how to coordinate the transmission and interference relationship between the primary and secondary nodes which are depicted in Fig.1.

## II. RELATED WORK

Many research works have been progressed to focus on this Cognitive Radio based ad hoc wireless Networks. In this survey, we focus our attention on recent research efforts related to primary and secondary network cooperation. We find that all these efforts only considered having the secondary network help relay traffic for the primary network. In [19], Simeone et al. proposed to have the primary network lease its spectrum in the time domain to the secondary network in exchange for having the secondary network relay its data.

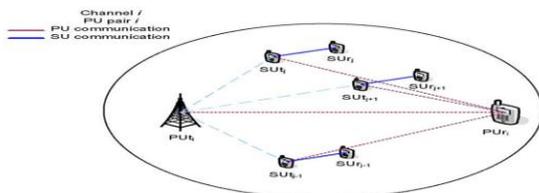
In [26], Zhang and Zhang formulated this model as a Stackelberg game and a unique Nash Equilibrium point was achieved for maximizing primary and secondary users' utilities in terms of their transmission rates and revenue. In [20], Su et al. proposed to have the primary network lease its spectrum in the frequency domain to the secondary network to relay its data in order to maximize primary users' energy saving and secondary users' data rates. In [10], Jayaweera et al. proposed a new way to encourage primary users to lease their spectrum by having secondary users place bids on the amount of power they are willing to expend for relaying primary users' traffic. In [9], Hua et al. proposed a MIMO-based cooperative CR network where the secondary users utilize MIMO's antenna diversity to help relay primary users' traffic while transmitting their own traffic. In [14], Manna et al. considered the three-node model in [11]. The relay node was assumed to be a secondary node and have MIMO capability. The primary transmitter leases the second time slot to the secondary node (relay node) so that the secondary node can use the time slot to help relay the primary node's traffic while transmitting its own data. In [15], Nadkar et al. considered how to offer incentive (in terms of time and frequency) to a secondary network to help transmit primary user traffic. They studied a cross-layer optimization problem that maximizes transmission opportunities for secondary users while offering a guaranteed throughput to the primary users. In all these efforts involving node-level cooperation between the primary and secondary networks, the focus has been limited to having secondary nodes help primary nodes in relaying primary users' traffic. As discussed, this is only a tip of the iceberg on network cooperation. In this paper, we envision much broader cooperation between the two networks.

## III. POLICY BASED NODE-LEVEL COOPERATION

The goal of this paper is to outline a broad vision of policy-based network cooperation between the primary and secondary networks as a new dimension in radio spectrum sharing. Here, a policy defines the scope of cooperation at the node-level between the two networks. Such cooperation policies could vary from unilateral cooperation (i.e., only secondary nodes help relay primary user traffic but not vice versa), bilateral cooperation, constrained cooperation, or other customized policy based on particular application needs or requirements.

As a concrete example, we consider the UPS policy which represents an interesting and extreme scenario where there is complete cooperation between the primary and secondary networks.

Fig. 2 illustrates the UPS policy for multi-hop primary and secondary networks. Unlike overlay, which is limited to only allowing secondary nodes help relay primary nodes' traffic, UPS allows primary nodes to help relay secondary nodes' traffic as well. From a network resource perspective, the UPS policy allows the pooling of all the resources from primary and secondary networks together and allows users in each network to access much richer network resources in a combined network.



**Fig 2: Cooperative Scenario of Primary and Secondary Nodes**

Note that although the two networks are combined into one at the physical level, priority or service guarantee to the primary network traffic can still be enforced by implementing appropriate traffic engineering rules.

It is not hard to see that there are many potential benefits associated with the UPS policy. We briefly describe these benefits as follows:

**Topology.** Comparing to having primary and secondary nodes being independent for each other, the combined network allows both primary and secondary networks a much improved connectivity with nodes from both networks.

**Power Control.** As more nodes fall in the maximum transmission range of a primary or secondary node, this node has more flexibility in choosing its next hop node via power control. This flexibility can be exploited for different upper layer performance requirements or objectives.

**Link Layer.** The improved physical topology allows more opportunities at the link layer for spectrum access. Both the primary and secondary networks can better coordinate with each other in transmission and interference avoidance. Further, the potential issue associated with link failure can now be mitigated effectively.

**Network Diversity.** The combined network offers more routing opportunities to users in both networks. This directly translates into improved throughput and delay performance for user sessions.

**Service and Applications.** The UPS architecture (combining both primary and secondary networks) allows to offer much richer services and applications than those services that were studied in [20], [26]. Although the two networks are combined, the services and applications offered to users in each network can still be supported, by implementing certain traffic engineering policies. In other words, the combined network does not mean that service guarantee to primary network will be lost. On the contrary, by specifying the desired resource management policy appropriately in the combined network, one can easily achieve various service differentiation objectives and application goals, as we shall describe in a case study in the rest of this paper.

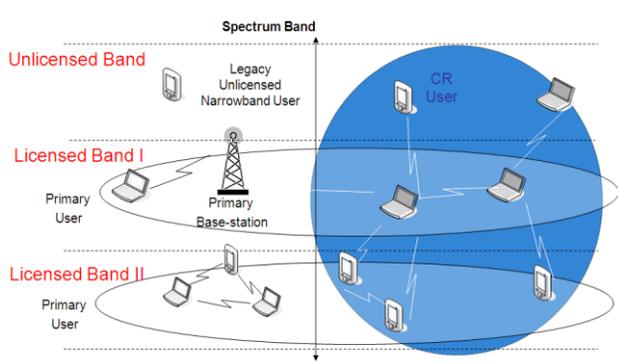
#### IV. PROBLEM SCOPE

In the rest of this paper, we offer an in-depth study of the UPS policy. Suppose that there is a set of sessions in the primary network, with each session having a certain rate requirement. In the secondary network, suppose there is also a set of sessions, with each session having an elastic traffic requirement. By “elastic”, we mean that each secondary session does not have a stringent rate requirement as the primary session. Instead, each secondary session will be supported on a best-effort basis and will transmit as much as the remaining network resource allows. A plausible goal under the UPS policy could be to have the combined network to support the rate requirements of the primary sessions while maximizing the throughput of the secondary sessions.

For this problem, there are a number of technical challenges that one must address:

- **Guaranteed service for primary traffic.** Since each primary session is assumed to have a hard rate requirement, the combined network should support it at all possibility. This problem alone may not be challenging. What is challenging (and interesting) is that should there are multiple ways to support primary sessions' rate requirements. We should find such a way that the rates for the secondary sessions are maximized in the combined network. It is shown in Fig:3

**Relay selection.** To meet the service requirement (guaranteed service for primary traffic) and to optimize the objective (maximize the rates of secondary sessions), relay node selection along a route (for either a primary or secondary session) is not a trivial problem.



**Fig:3 Spectrum Sensing and channel allocation**

**Scheduling.** To maximize the rates of the secondary sessions while guaranteeing the rates of the primary sessions, scheduling in each time slot needs to be carefully designed. In particular, in addition to addressing traditional self-interference (half-duplex) and mutual-interference problems, the primary network must be cooperative so as to help the secondary sessions to achieve their optimization objective in the combined network. Such cooperative behavior from the primary network is a key in the UPS policy and has not been explored in prior efforts.

#### Mathematical Modeling

In this section, we develop a mathematical model for the UPS policy. In Cognitive Radio Network, the uncertain availability of the free white space spectrum is a unique feature of CRNs. The channel state or white space spectrum information available to the secondary or Unlicensed users is described by a probability vector of Free Space  $W_n^{(f)} = [W_1^{(f)}, W_2^{(f)}, \dots, W_N^{(f)}]$  where  $W_n^{(f)}$  is the probability that denotes  $n$  channel or white space spectrum is free. We assume that this information is obtained either by sensing the white space spectrum or free channel, or through knowledge of the traffic statistics of the primary users, or a combination of both. Let  $N$  is the number of the available sub-channels,  $M$  is the number of assigned sub-channels in scheduling period ( $M = T_{sp}/L$ ) where  $T_{sp}$  is scheduling period and  $L$  is the time slot length,  $r(n) = 1, 2, \dots, N$  the number of remaining free slots of sub-channel  $n$  (at the beginning of each scheduling period ( $r(n) = M$ )),  $K$  the total number of SUs, and  $q(i, j)$  the traffic queue of user  $i$  and traffic class  $j$

#### Priority calculation

In the first step, the priority function is calculated in order to sort the traffic queue based on the QoS in Secondary nodes and the type of traffic. The priority of user  $i$  requesting traffic class  $j$  is expressed as follow:

$$P(i, j) = c_j \exp\left[\alpha_j \frac{w_{ij}(t) - T_j}{T_j} - \beta_j \frac{b_{ij}}{R_j L}\right]$$

where  $c_j$  is the adaptive service coefficient for the Secondary users in Cognitive Radio Network,  $\alpha_j$  and  $\beta_j$  are weights for balancing delay, traffic and throughput of the Secondary users ( $\alpha_j + \beta_j = 1$ ),  $T_j$  and  $R_j$  are maximum packet delay induced and bit rate of Secondary Users traffic class  $j$ ,  $L$  is the time slot length  $w_{ij}(t)$  is the waiting time of the Secondary user  $i$  with traffic class  $j$  has incurred since its arrival until being served at time  $t$ ,  $b_{ij}$  is the target number of bits to be transmitted by the Secondary user  $i$  for traffic class  $j$ .

In Cognitive Radio network the users are classified into Licensed Primary Users and Unlicensed Secondary Users and there is no dedicated channel to send data, sensors need to negotiate with the neighbors and select a channel for data communication in Cognitive Radio Wireless networks. This is a very challenging issue, because there is no cooperation between the PUs and SUs. PUs may arrive on the channel any time. If the PU claims the channel, the SUs have to leave the channel immediately. Therefore, data channels should be selected intelligently using Priority Based Selection algorithms considering the PU's behavior on the channel and the traffic in Secondary Users.

Therefore Priority Based Selection algorithms has been shown to effectively improve self-coexistence jointly in spectrum utilization, power consumption, and intra-cell fairness.

We consider a 30-node network, with 15 primary nodes and 15 secondary nodes randomly deployed. The location of each node is given in Table 1. In this example, we assume that there are two primary sessions in the primary network and two secondary sessions in the secondary network. The source and destination nodes for each session are randomly chosen in each network. The utility maximization problem for the secondary sessions under the interweave paradigm can be formulated following a similar token to OPT.

Table 2 shows the approximation gap between the utility objective of the linearized problem and the utility objective of the original problem under different  $R^{\delta 1P}$  and  $R^{\delta 2P}$ . The first column represents increasing rate requirements for the primary sessions. The second column shows the utility objectives of the two secondary sessions (abbreviated as "SS" in the table) from the linearized problem OPT-L, while the third column shows the utility objectives of the two secondary sessions from the original problem. The fourth column shows the gap between the utility objectives from the linearized problem and the original problem.

Given the target approximation error  $\epsilon \approx 0.02$ , all actual approximation errors fall below this target.

Table 3, Table 4 and Table 5 summarize the results of this study. The tables represent increasing rate requirements for the primary and secondary nodes of the network. The UPS policy is depicted in Fig:4.

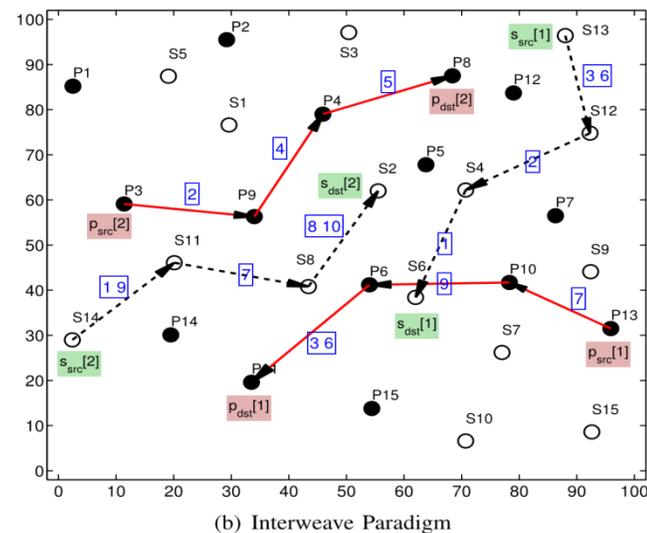
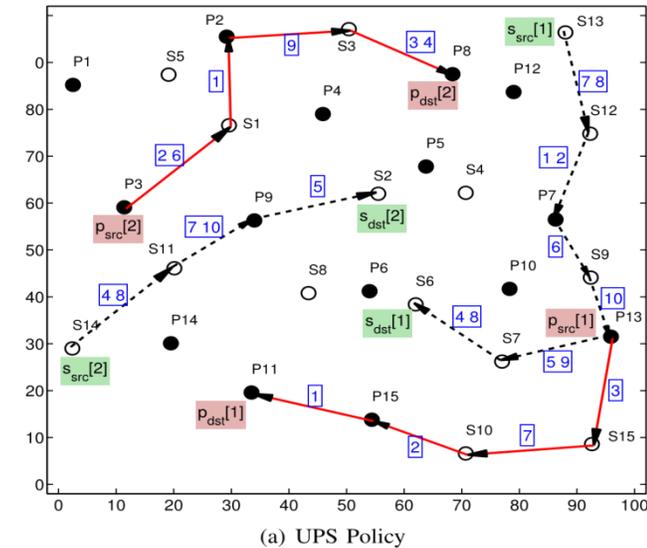


Fig. 4. Region 1 example that showing the flow routing topologies and

**Table 1**  
**Location of Primary and Secondary Nodes for the 30-Node Network**

Primary Node	Location	Secondary Node	Location
P <sub>1</sub>	(2.5, 85.2)	S <sub>1</sub>	(29.6, 76.6)
P <sub>2</sub>	(29.2, 95.5)	S <sub>2</sub>	(55.5, 62)
P <sub>3</sub>	(11.4, 59.1)	S <sub>3</sub>	(50.4, 97.1)
P <sub>4</sub>	(45.9, 79)	S <sub>4</sub>	(70.7, 62.2)
P <sub>5</sub>	(63.8, 67.8)	S <sub>5</sub>	(19.1, 87.4)
P <sub>6</sub>	(54, 41.2)	S <sub>6</sub>	(62, 38.4)
P <sub>7</sub>	(86.3, 56.5)	S <sub>7</sub>	(77, 26.2)
P <sub>8</sub>	(68.4, 87.5)	S <sub>8</sub>	(43.4, 40.8)
P <sub>9</sub>	(34, 56.3)	S <sub>9</sub>	(92.4, 44.1)
P <sub>10</sub>	(78.3, 41.7)	S <sub>10</sub>	(70.7, 6.6)
P <sub>11</sub>	(33.5, 19.6)	S <sub>11</sub>	(20.1, 46.1)
P <sub>12</sub>	(79, 83.7)	S <sub>12</sub>	(92.3, 74.8)
P <sub>13</sub>	(95.9, 31.5)	S <sub>13</sub>	(88, 96.4)
P <sub>14</sub>	(19.5, 30.1)	S <sub>14</sub>	(2.4, 29)
P <sub>15</sub>	(54.4, 13.8)	S <sub>15</sub>	(92.6, 8.6)

**Table 2**  
**Approximation Gap Between the SS Utility Objectives of Linearized Problem and Original Problem**

Rate Requirement R <sup>δ1P</sup> ; R <sup>δ2P</sup>	SS Utility of Linearized Problem	SS Utility of Original Problem	Gap
0	3.7012	3.7128	0.0016
0.2	3.288	3.3046	0.0016
0.4	3.288	3.3046	0.0016
0.6	3.288	3.3046	0.0016
0.8	3.288	3.3046	0.0016
1.0	3.288	3.3046	0.0016
1.2	3.288	3.3046	0.0016
1.4	3.288	3.3046	0.0016
1.6	3.288	3.3046	0.0016
1.8	3.158	3.167	0.0009
2.0	3.158	3.167	0.0009
2.2	3.158	3.167	0.0009
2.4	3.158	3.167	0.0009
2.6	2.892	2.899	0.007
2.8	2.653	2.656	0.003
3.0	2.653	2.656	0.003
3.2	2.653	2.656	0.003
3.4	2.653	2.656	0.003
3.6	2.653	2.656	0.003
3.8	2.653	2.656	0.003
4.0	2.288	2.305	0.017
4.2	2.288	2.305	0.017
4.4	2.183	2.191	0.008
4.6	1.969	1.981	0.012
4.8	1.969	1.981	0.012

**TABLE 3**  
**Performance Comparison Between the UPS Policy and the Interweave Paradigms for Different Primary Session Rate Requirements**

Rate Requirements	UPS		Interweave Paradigm	
	Feasible in PN	Utility/SS	Feasible in PN	Utility/SS
0	Yes	3.7012	Yes	3.0402
0.2	Yes	3.288	Yes	1.899
0.4	Yes	3.288	Yes	1.899
0.6	Yes	3.288	Yes	1.899
0.8	Yes	3.288	Yes	1.899
1.0	Yes	3.288	Yes	1.899
1.2	Yes	3.288	Yes	1.263

**Table 4**  
**Feasibility Performance of the Primary Sessions and Utilities of the Secondary Sessions Under Increasing Number of the Primary Sessions**

Number Of Primary Session	UPS		Interweave Paradigm	
	Feasible in PN	Secondary Utility	Feasible in PN	Secondary Utility
0	Yes	3.69	Yes	2.219
1	Yes	3.446	Yes	1.693
2	Yes	3.058	Yes	0.931
3	Yes	2.661	Yes	0.805
4	Yes	2.118	Yes	1
5	Yes	0.83	Yes	1
6	Yes	1	No	N/A
7	Yes	1	No	N/A
8	No	N/A	No	N/A

**Table 5**  
**Secondary Sessions' Utility Values Under Increasing Number of the Secondary Sessions**

Number of Secondary Session	UPS	Interweave
1	2.228	1.355
2	3.21	2.852
3	4.594	2.652
4	4.738	0.943
5	4.253	1
6	2.418	1
7	2.307	1
8	1.134	1
9	1	1

From the tables, it is estimated that whether the additional new primary session can be accommodated (feasible) under UPS and interweave, respectively.

Comparing these values, we can find that the maximum number of the primary sessions under UPS (7) is larger than that under interweave (5). The third and fifth columns show the utility function of the secondary sessions under UPS and interweave. Comparing these table values, we can see that UPS achieves higher utility objectives than interweave. In summary, both primary and secondary sessions benefit more from UPS than interweave.

Now we do the converse. Suppose there are two primary sessions, with each session's source and destination nodes being  $\delta P_9; P_{17}$  and  $\delta P_{11}; P_{15}$ , respectively. The data rate requirement for each primary session is 1.8. By keeping these primary sessions fixed, we increase the number of secondary sessions. The source and destination nodes of each additional secondary session is randomly chosen from the remaining secondary nodes. Once chosen, we add it on top of the existing secondary sessions. Table 5 shows our results. The first column in the table shows the increasing number of secondary sessions. The second and third columns show the utility values of the secondary sessions under UPS and interweave, respectively. Comparing these two columns, we can find that the maximum number of the secondary sessions that can be supported under UPS (8) is larger than that under interweave (4). Further, for the same number of secondary sessions (from 1 to 8), the achieved utility value under UPS is higher than that under interweave.

## V. CONCLUSION AND FURTHER WORK

In this paper, we develop a policy-based network cooperation paradigm as a new dimension for spectrum sharing between the primary and secondary users. Such network cooperation can be defined as a set of policies under which different degrees of cooperation are to be achieved. The benefits of this paradigm are numerous, including improved network connectivity and spatial diversity, increased flexibility in scheduling and routing, cost savings in infrastructure needed for each individual network, among others. For the purpose of performance study, we consider a specific policy called UPS, which allows a complete cooperation between the primary and secondary networks at the node level to relay each other's traffic. We studied a problem with the goal of supporting the rate requirement of the primary network traffic while maximizing the throughput of the secondary sessions. Through rigorous mathematical modeling, problem formulation, approximation solution, and simulation results, we showed that the UPS offers significantly better throughput performance than that under the interweave paradigm.

In our future work, we will explore other policies under the policy-based network cooperation paradigm. Under a given policy, data forwarding behavior may also be affected by user requirements and performance objectives. Such user requirements and performance objectives under a particular policy are many, and each scenario would result in different data forwarding for both the primary and the secondary sessions. Clearly, there is a large landscape for further research under this new paradigm. We hope our vision and results in this paper will open the door for further research in this area.

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