Chapter 5

Power-Bandwidth Exchange Based Resource Allocation for Distributed Cooperative Network

Pricing approach for resource allocation and cooperation encouragement has been presented in the previous chapter. Another powerful approach to bind nodes in cooperation is to make pair of nodes having complementary resource and allow them to exchange their resource to enhance performance of both. This mechanism is applicable in self-organizing adaptive network, where nodes are capable to estimate amount of exchange for cooperation and reassign its resources to others. In order to make the cooperation completely independent and distributed process, resource exchange mechanism is proposed in this chapter.
5.1 Resource Exchange for Cooperation

The essence of cooperative communication lies in the mechanism in which the nodes cooperate with each other without any external force. A scenario can be assumed where the nodes evaluate their own shortcoming and find out partner having complementary need in the vicinity. Both the nodes interact with each other and determine the amount of resource to be exchanged. This type of exchange is beneficial to both of them and therefore, they would remain in cooperation as long as they find benefit. This mechanism demands decision making capability and adaptability in the nodes. Wireless nodes in the advanced network possess higher processing power. They can be programmed to take decision to manage the resources to achieve better performance and save resources. Such nodes form a pair having complementary resource and share the resource owned by them with their partner. Thus, they remain in cooperation without the need of any outside stimulation like pricing, credit or reputation. Success of this cooperation scheme depends on target performance metrics, channel gains between each node pairs, power availability, and bandwidth and/or time slot availability in the network. The proposed framework takes into account all these parameters for successful resource exchange based cooperation. For forming successful cooperative pair, nodes need to negotiate with each other and decide amount of resource to be exchanged within the limit of availability of resource.

The exchange of resource can be bandwidth and/or time slot with power (Simeone) (Toroujeni) (D. R. Zhang) (Jayaweera) (Xu) or bandwidth with bandwidth (C. H. Zhang). With the emergence of advanced wireless communication networks like cognitive radio, device to device (d2d) communication and heterogeneous network, it is expected that the wireless node would communicate even when the node is unlicensed or out of the coverage of parent network. In this scenario, exchange of bandwidth and/or time slot with retransmission power (relaying) seems more practical. However, the concept of exchange of bandwidth with bandwidth or power with power is also possible. In this chapter, the exchange of bandwidth/time division with relaying power is undertaken. A node in need of extra bandwidth puts forward the offer of relaying power to retransmit information of other node in exchange of bandwidth. In this mechanism, nodes themselves would take decision about optimum resources to be employed in cooperative mode to meet individual targets. Nodes require to know only the local channel state information and make quick decision about feasibility of cooperation in their vicinity.
The success of this mechanism lies in finding the suitable partner, in the vicinity, with suitable interdependent need of resource. Our objective is to design distributed, low overhead resource exchange mechanism to search suitable partner and determine the amount of resource to be exchanged. A simplified and one-shot negotiation procedure is developed in this chapter where nodes can reach a deal of resource exchange quickly and accurately. Proposed framework stimulates and binds the nodes in cooperation, saves energy, increases data rate and hence proves to be resource efficient.

Futuristic wireless network consisting of variety of nodes, engaged in delay tolerant applications is considered in this proposal. Nodes make the pair in their vicinity to exchange bandwidth with relaying power. This exchange results in improved coverage, enhanced data rates and power saving of the nodes in the network. Proposed mechanism is suitable for d2d communication, ad hoc network and cognitive radio network where nodes are delegated the power to make decisions about routing, data handling, resource management, packet forwarding etc.

5.2 System Model

A futuristic wireless network consisting of $i, i \in \{1, 2, \ldots, M\}$ self-organizing nodes ready to share bandwidth/time acting as source nodes and $j, j \in \{1, 2, \ldots, N\}$ self-organizing nodes ready to become relay is considered. The destinations of source nodes and relay nodes are assumed to be different. The nodes are capable of making the decision of cooperation, degree of cooperation and resource optimization by sensing the channel locally. The network nodes are considered to employ Amplify and Forward (AF) protocol of cooperative communication. However, the mechanism is applicable to Decode and Forward (DF) protocol as well.

Fig 5.1 represents a typical scenario of $i$ source nodes communicating with their destination $Ds$ and $j$ relay nodes want to communicate with their destination $Dr$. $Ds$ and $Dr$ can be the same node. Source nodes want to achieve data rate $R_{si}^{tar}$ with $W$ units of bandwidth allocated to them.
With limited power and bad channel condition, it is not possible to achieve target data rate on its own. Hence, source nodes seek cooperation of relay to retransmit and take benefit of diversity combining at the destination, $D_s$. Relay nodes, having their target data rate $R_{fj}^{tar}$, can be unlicensed nodes of cognitive radio or nodes out of coverage from parent network or nodes involved in d2d communication. Such nodes are in need of spectrum to carry on their own communication with destination $Dr$. Such nodes would be involved in exchange with offer of power to retransmit in exchange of a fraction of bandwidth.

Fig 5.1 System Model for M sources and N relays
Table 5.1 Notations

<table>
<thead>
<tr>
<th>Notation</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{si}^{NC}$</td>
<td>Data rate achieved by source $i$ without cooperation</td>
</tr>
<tr>
<td>$R_{si}^{tar}$</td>
<td>Target data rate of source $i$ with resource exchange</td>
</tr>
<tr>
<td>$R_{si}^{C}$</td>
<td>Data rate achieved by source $i$ with cooperation</td>
</tr>
<tr>
<td>$R_{rj}^{NC}$</td>
<td>Data rate achieved by relay $j$ without cooperation</td>
</tr>
<tr>
<td>$R_{rj}^{tar}$</td>
<td>Target data rate of relay $j$ with resource exchange</td>
</tr>
<tr>
<td>$R_{rj}^{C}$</td>
<td>Data rate achieved by relay $j$ with cooperation</td>
</tr>
<tr>
<td>$h_{si}^{SD}$</td>
<td>Channel gain of source-destination of source link of source $i$</td>
</tr>
<tr>
<td>$h_{ij}^{SR}$</td>
<td>Channel gain of source-relay link of source $i$</td>
</tr>
<tr>
<td>$h_{ij}^{RD}$</td>
<td>Channel gain of relay-destination of source link</td>
</tr>
<tr>
<td>$h_{ij}^{RDr}$</td>
<td>Channel gain of relay-destination of relay link</td>
</tr>
<tr>
<td>$\Gamma_{i}^{SD}$</td>
<td>Signal to noise ratio of source-destination of source link of source $i$</td>
</tr>
<tr>
<td>$\Gamma_{i}^{SR}$</td>
<td>Signal to noise ratio of source-relay link of source $i$</td>
</tr>
<tr>
<td>$\Gamma_{ij}^{RDs}$</td>
<td>Signal to noise ratio of relay-destination of source link of source $i$</td>
</tr>
<tr>
<td>$\Gamma_{ij}^{RDr}$</td>
<td>Signal to noise ratio of relay-destination of relay link of relay $j$</td>
</tr>
<tr>
<td>$\Gamma_{i}^{AF}$</td>
<td>Signal to noise ratio of S-R-DS two hop AF cooperative link</td>
</tr>
<tr>
<td>$\Gamma_{i}^{DF}$</td>
<td>Signal to noise ratio of S-R-DS two hop DF cooperative link</td>
</tr>
<tr>
<td>$P_{si}$</td>
<td>Power transmitted by source $i$</td>
</tr>
<tr>
<td>$P_{si}^{NC}$</td>
<td>Power required by source $i$ to reach target without cooperation</td>
</tr>
<tr>
<td>$P_{Rj}^{total}$</td>
<td>Power available with relay $j$</td>
</tr>
<tr>
<td>$P_{RS_{ij}}$</td>
<td>Relay power used for re-transmission of source signal</td>
</tr>
<tr>
<td>$P_{RR_{ij}}$</td>
<td>Relay power used for own transmission</td>
</tr>
<tr>
<td>$W_{si}^{total}$</td>
<td>Bandwidth available with source $i$</td>
</tr>
<tr>
<td>$W_{si}$</td>
<td>Bandwidth used by source $i$ for own transmission</td>
</tr>
<tr>
<td>$W_{rj}$</td>
<td>Bandwidth allocated to relay $j$ in exchange of cooperation</td>
</tr>
<tr>
<td>$W_{si}^{min}$</td>
<td>Minimum bandwidth needed by the source $i$ for given $P_{RS_{ij}}$</td>
</tr>
<tr>
<td>$n_{R}, n_{D}$</td>
<td>Additive White Gaussian Noise at relay and destination with variance $\sigma_{R}^{2}$ and $\sigma_{D}^{2}$, respectively</td>
</tr>
<tr>
<td>$\tau$</td>
<td>Time slot allocated to source for its transmission</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Fraction of time $\tau$ during which source transmits in phase I ($0 &lt; \beta &lt; 1$)</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Fraction of power $P_{rj}^{total}$ used for re-transmission of source signal</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Path loss exponent ($\gamma = 3$)</td>
</tr>
<tr>
<td>$N_{0}$</td>
<td>Average noise power</td>
</tr>
<tr>
<td>$\psi$</td>
<td>Energy saving of source</td>
</tr>
</tbody>
</table>
5.3 Bandwidth-Power Exchange Mechanism

Source $i$ is allocated bandwidth $W$ units for time slot of $\tau$ unit. Source $i$ realizes that $R_{si}^{NC} < R_{si}^{tar}$. The source is unable to achieve target data rate of $R_{si}^{tar}$ without cooperation. On the other side, a node $j$ is deprived of bandwidth and wants to achieve data rate of $R_{rj}^{tar}$. The procedure of determining suitable partner is initiated by either source or relay, as discussed in section 5.5. The source offers bandwidth $W_{rj} (< W_{si}^{total})$ to the relay as an incentive for retransmitting information of the source. Source decides to transmit in $W_{si} (= W_{si}^{total} - W_{rj})$ bandwidth.

The bandwidth $W_{si}$ is divided in two parts in time slot of duration, $\tau$ as shown in Fig 5.2. In $(1 - \beta)$ fraction of time slot, the source transmits its own signal. The relay receives it, amplifies, and forwards it in remaining $\beta$ fraction of the time slot $\tau (0 < \beta < 1)$. The source transmits only on $W_{si}$ bandwidth for $(1 - \beta)$ fraction of the time slot. The relay transmits own signal on bandwidth $W_{rj}$ for the entire time slot and the signal of the source on bandwidth $W_{si}$ for $\beta$ fraction of the time slot. In this way, the relay allocate transmission power for relaying source’s signal in exchange of the bandwidth.

In proposed exchange mechanism, a relay is ensured a fraction of bandwidth for full duration of time slot, which in turn, ensures target data rate to the relay. Source can save significant amount of energy in proposed technique by transmitting in fraction of the bandwidth for fraction of the time only. One source and one relay are involved in exchange so both the nodes get significant amount of benefit in terms of data rate and energy saving for source node and spectrum for transmission for relay node. Moreover, this technique needs less overheads as it requires only the local channel state information. A mathematical modelling of the proposed resource exchange scheme is presented in following subsection.
Source transmits in $W_{si} = W_{si}^{total} - W_{rj}$ in time $(\beta \times \tau)$ with power $P_{Si}$

Source transmits in $W_{si} = W_{si}^{total} - W_{rj}$ in time $(1 - \beta) \times \tau$ with power $P_{RSji} = (\alpha \times P_{Rj}^{total})$

Source $i$ assigns bandwidth $W_{rj}$ to relay for entire time, $\tau$.
Relay $j$ transmits own information at power $P_{RRjj}$

Fig 5.2 Bandwidth-power exchange mechanism

5.3.1 Data Rate of Source with and without Cooperation

Source $i$ has bandwidth $W_{si}^{total}$ unit available for time $\tau$ and power $P_{Si}$. It wants to achieve the data rate of $R_{si}^{tar}$ units. Maximum data rate that source $i$ can achieve at a given instant depends on signal to noise ratio of the given source $S$ - destination of source $Ds$ ($S-Ds$) link. Achievable data rate without cooperation can be given as
$$R_{si}^{NC} = W_{si}^{total} \ast \log_2 (1 + \Gamma_i^{SDs}) \tag{5.1}$$

where, $\Gamma_i^{SDs}$ is signal to noise ratio ($= \frac{P_{Si} h_i^{SDs}}{N_0}$) and $h_i^{SDs}$ is the channel gain of $S-Ds$ link.

If data rate without cooperation, $R_{si}^{NC} < R_{si}^{tar}$, source decides to cooperate with relay by sparing $W_{rj}$ bandwidth, a fraction of total bandwidth $W_{si}^{total}$, and use it to attract suitable relay. After sparing $W_{rj}$, the bandwidth available with the source for its own transmission is $W_{si} = W_{si}^{total} - W_{rj}$. The source finds the relay and determines the amount of resource to be exchanged. Detail mechanisms for resource exchange are presented in following sub-sections. The cooperative transmission is carried out in two phases:

1. In phase I of time duration $(\beta \ast \tau)$, source transmits in bandwidth $W_{si}$ with power $P_{Si}$.

2. In phase II of time duration $1-(\beta \ast \tau)$, relay re-transmits the amplified version of the signal in $W_{si}$ bandwidth using power $P_{RS_{ji}}$.

The relay transmits own signal on $W_{rj}$ bandwidth, which is spared by the source as an incentive, at power of $P_{RR_{jj}}$. Destination of source receives the signal from source in phase I and from the relay in phase II and combines them using Maximal ratio combining (MRC). For simplifying the process at the relay, the time slot is divided in two equal parts by setting $\beta = 0.5$. However, any other value of $\beta$ can be considered when relay applies decoding and re-encoding the signal at different rate. Signal to noise ratio of two hop channel through relay can be given as,

$$\Gamma_i^{AF} = \frac{1}{N_0} \left( \frac{P_{Si} | h_i^{SRi} |^2 + P_{RS_{ji}} | h_j^{RDI} |^2}{P_{Si} | h_i^{SRi} |^2 + P_{RS_{ji}} | h_j^{RDI} |^2 + N_o} \right) \tag{5.2}$$

Data rate achieved by Amplify and Forward protocol at relay and MRC at destination can be given as,

$$R_{si}^{C} = 0.5 \ast W_{si} \ast \log_2 (1 + \Gamma_i^{SDs} + \Gamma_i^{AF}) \tag{5.3}$$
In (5.3), 0.5 indicates that source and relay transmit for equal half of the time slot by setting $\beta = 0.5$. The value of $P_{RSji}$ in (5.2) and $W_{si}$ in (5.3) are determined by source and the relay during the cooperation establishment process so that $R_{si}^C \geq R_{si}^{tar}$.

5.3.2 Determination of Bandwidth $W_{rj}$ and $W_{si}$

The source and relay nodes are interested in achieving the data rate more than or equal to $R_{si}^{tar}$ and $R_{rj}^{tar}$, respectively. Both the nodes would participate in cooperation, if the bandwidth offered by the source and re-transmission power offered by the relay are sufficient for the nodes to achieve their targets. Division of bandwidth between source and relay is within the constraint of maximum available bandwidth of $W_{si}^{total}$ of the source. Similarly, the relay spares power for retransmitting source’s signal, $P_{RSji}$ and power for own transmission, $P_{RRj}$. Sum of these both cannot be more than available total power $P_{Rj}^{total}$.

Minimum bandwidth required by the source, $W_{si}^{min}$ to reach target can be given by substituting $R_{si}^C = R_{si}^{tar}$ in (5.3) and re-arranging,

$$W_{si}^{min} = \frac{2^{2R_{si}^{tar}}}{\log_2 \left[ 1 + \frac{P_{SI}|h_{SI}|^2}{N_0} + \frac{1}{N_0} \left( \frac{P_{SI}|h_{SR}|^2 + P_{RSji}|h_{RDS}|^2}{P_{SI}|h_{SI}|^2 + P_{RSji}|h_{RDS}|^2 + N_0} \right) \right]}$$

(5.4)

In determination of minimum bandwidth in (5.4), source requires the knowledge of power with which relay would retransmit, $P_{RSji}$ and channel gains. Source offers remaining bandwidth, $W_{rj} = W_{si}^{total} - W_{si}$ to relay. Relay uses this bandwidth for entire duration $\tau$ and transmits own signal with power $P_{RRj}$. Relay calculates the maximum data rate achieved with this bandwidth based on its power budget.

$$R_{rj}^C = W_{rj} \log_2 \left( 1 + \frac{P_{RRj}|h_{RD}|^2}{N_0} \right)$$

(5.5)
As long as data rate with cooperation $R_{rj}^C \geq R_{rj}^{tar}$, cooperative transmission continues. Due to change in channel gains or reduction in available power or increase in target data rate, if cooperation data rate reduces below target data rate, cooperation seizes. The source node $i$ and relay node $j$ have to redistribute bandwidth and power to sustain cooperation. In the process of redistribution, if none of the combinations of bandwidth-power exchange seems feasible, the nodes have two options: (1) to continue cooperation with data rate less than target, and (2) to initiate the procedure for searching for partner.

### 5.3.3 Relay Power Budget and Source Power Saving

Relay has limited power $P_{Rj}^{total}$ available with it. It uses power $P_{RRjj}$ for its own transmission for $\tau$ duration and power $P_{RSji}$ to cooperate with source during $\tau/2$ duration as shown in (5.4) and (5.5). Let relay spare $\alpha$ fraction of power $P_{Rj}^{total}$ for source and use remaining $(1 - \alpha)$ fraction for itself, i.e.

$$P_{RSji} = \alpha * P_{Rj}^{total} \quad \text{and} \quad P_{RRjj} = (1 - \alpha) * P_{Rj}^{total} \quad 0 < \alpha < 1 \quad (5.6)$$

From (5.4), (5.5) and (5.6), it can be seen that possibility of cooperation between a pair of nodes depends on target data rate of both the nodes, available resources with both the nodes and channel gains between the nodes. These parameters are used to find matching partner.

Another motivation for the source node is to save the power by opting for cooperation. If the source $i$ tries to achieve target data rate $R_{si}^{tar}$ directly, it requires power $P_{si}^{NC}$. If power available with source is $P_{si} < P_{si}^{NC}$, source opts for the cooperation of relay. Power required by the source in direct transmission to achieve the target can be given by re-arranging (5.1) as

$$P_{si}^{NC} = \frac{N_o}{|h_{si}^{SDS}|^2} * \left( \left\lfloor \frac{R_{si}^{tar}}{W_{si}^{total}} \right\rfloor - 1 \right) \quad (5.7)$$

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In case $P_{Si} > P_{si}^{NC}$, then also source can choose cooperation mode to save energy. This exchange mechanism would result in saving of the energy for the source node. In direct transmission, the source node would spent power $P_{Si}^{NC}$ in $W_{si}^{total}$ units of the bandwidth for time duration $\tau$, whereas in cooperative mode, it spend $P_{Si}$ power in $W_{si}$ units of bandwidth ($W_{si} < W_{si}^{total}$) for $\tau/2$ duration only. Energy saving in cooperative mode compared to direct transmission can be given as

$$\psi = \left( P_{si}^{NC} \times W_{si}^{total} \times \tau \right) - \left( P_{si} \times W_{si} \times \tau/2 \right)$$

(5.8)

It is, therefore, in benefit of source to go for cooperation to save energy, if suitable relay is available in the vicinity.

### 5.4 Performance Evaluation and Discussion

Extensive simulation are carried out to evaluate the performance of the proposed mechanism. Amount of resource to be exchanged to fulfil the requirements of target data rate of source and relay is determined. The performance is tested over the random channel variations also to prove that the cooperation of this type is long lasting. Energy saved by the source node is calculated to emphasis on the benefit of cooperation.

#### 5.4.1 Simulation Environment

To demonstrate the resource exchange mechanism, a four node network is considered as shown in Fig 5.3. Node S establishing the link with its destination $Ds$ finds it difficult to reach target data rate using its available power. There is a node $R$, without any bandwidth resource, wants to communicate with its destination $Dr$. Such nodes make pair with each other using the procedure, discussed in section 5.5. The node with spectrum behaves as source node and node without bandwidth acts as relay to retransmit source node’s signal in exchange of a fraction of bandwidth.
The distance between source $S$ and relay $R$ is 100 units, relay $R$ and destination of source $Ds$ is 100 units, source $S$ and destination of source $Ds$ is 200 units and relay $R$ and destination of relay $Dr$ is 150 units. For the sake of simplicity, path loss channel model with exponent 3 is assumed in which channel gain is inversely proportional to the distance between the nodes. The relay is assumed to employ AF protocol. Source power $P_S$ and relay power $P_{R\text{ total}}$ are 2 units and 5 units respectively. Bandwidth available with Source is 10 units. Simulation model is presented in Fig 5.3.

![Fig 5.3 Simulation Model](image)

### 5.4.1 Relay’s Demand Curves for Different Target Data Rate of Source

The degree of cooperation depends on the resource available with nodes and their target data rates. If the source wants to achieve higher target of data rate and it has less power of its own, it wants relay to cooperate with more power. In turn, the relay wants large portion of bandwidth to remain in cooperation. Therefore, both the nodes have to reach to a compromise where both can achieve their individual target within the limitation of their resources. Fig 5.4 shows the exchange of relaying power $P_{RS}$ with fraction of bandwidth $W_r$ as a function of target data rate $R_{S\text{ tar}}$ of the source. Source calculates minimum bandwidth required for own transmission $W_{S\text{ min}}$ for a given value of $P_{RS}$ using (5.4), and offer remaining bandwidth, $W_r$ to relay as an incentive.

When source target data rate is 1bit/unit, source would offer bandwidth from 5.2 to 7.3 units in exchange of relay power from 1 to 4.5 units. When source target is 2 bits/unit, source keeps more bandwidth with it and offers bandwidth from 0.2 to 4.7 units in exchange of relay power.
from 1 to 4.5 units, respectively. Source offers more bandwidth if exchange of more power is reciprocated. The dark curve shows the demand of the relay for achieving its target data rate of 1 bit/unit. Intersection of the dark curve with the set of curves of source’s offer indicates the possible resource exchange for cooperation for the given target data rate of the source and the relay.

5.4.2 Relay’s Demand Curve for Different Target Data Rate of Relay

Similar situation from relay’s perspective is demonstrated in Fig 5.5. When target data rate of relay is 0.7 bit/unit, it demands bandwidth form 1 to 6.5 in exchange of relaying power from 1 to 4.5. The demand of relay changes from 1.9 to 11.9 in exchange of relaying power from 1 to 4.5 for target data rate of 1.2 bits/unit. If relay’s demand exceeds available resource with source, cooperation would not be possible. This issue is to be taken care while establishing the cooperation during negotiation process. The dark curve shows source’s offer to relay and the intersection point is the possible resource exchange for successful cooperation.

Fig 5.4 Relay power against bandwidth with relay target fixed at 1 bit / unit
Fig 5.5 Offer of relay power for bandwidth for source target fixed at 2 bits/unit

5.4.3 Analysis of Range of Equilibrium of Resource Exchange

Relay offers $\alpha, (0 < \alpha < 1)$ portion of its power $P_R^{total}$ to retransmit source’s signal as mentioned in (5.6). The range of $\alpha$ for successful cooperation is depicted in Fig 5.5 for different values of relay target data rate. Without cooperation, the source is in position of achieving data rate of 1.7 bit/unit of bandwidth using own power $P_S$ and bandwidth $W_s^{total}$ in direct transmission. It wants to get 2 bits/unit of bandwidth. Therefore, search for suitable relay to offer a fraction of bandwidth to engage it in cooperative re-transmission.

In turn, the relay promises to use $P_{RS} = \alpha * P_R^{total}$ for source signal re-transmission. Fig 5.6 shows data rate achieved by the source, when relay spares different portion of power in exchange of bandwidth. For example, if relay offers small amount of relaying power by setting $\alpha = 0.1$ for source signal re-transmission and demands more bandwidth, source would not be able to achieve target data rate. Source can achieve the target for the range of $\alpha$ from 0.4 to 0.7, even if relay target changes from 0.8 to 1.2. This range of $\alpha$ provides stable cooperation.
5.4.4 Analysis of Energy Saving for Source

For the source node, the cooperation would result in saving of the energy as shown in (5.7) and (5.8). Suppose, the source node is not power constrained. To achieve target, it has to transmit more power per unit in W units of bandwidth for full time slot. In cooperative mode, it transmit less power for $W_s < W$ units of bandwidth and for half of the slot (considering $\beta = 0.5$) as shown in Fig 5.2

By participating in cooperation, it could save energy to prolong its lifetime without recharging the battery. Fig 5.7 shows the power spent by the source in direct transmission mode and cooperative mode with respect to available source power, $P_s$ for different degree of cooperation from the relay node. In direct transmission mode, the energy spend by the source linearly varies with available source power from 1 to 2 units. When relay node helps by sparing 0.2 portion of its power ($\alpha = 0.2$), energy consumed in cooperative mode varies from 8 units to 10 units as available source power varies from 1 unit to 2 unit.
For $\alpha = 0.8$, source spends energy from 4.6 to 5.8 units as source power varies from 1 unit to 2 units. Source spends less energy of its own if $\alpha$ is large. This is because when $\alpha$ is small, relay cooperates with less power so it would get less bandwidth in exchange and source would be transmitting in large bandwidth so energy spent by the source is more compared with the case of large $\alpha$. Therefore, the energy saving by the source varies between 21% to 54% for $P_s = 1$ and 51.7% to 71.5% for $P_s = 2$.

Fig 5.7 Energy spent by source node in direct mode and cooperative mode

5.4.5 Stable Cooperation in Case of Channel Variations

Exchange of resources for mutual gain depends on channel gain of inter-node links. When nodes are mobile, the change in their location causes channel gain to change. In this exchange mechanism, nodes stick to cooperative behaviour under the condition of mobility. For including
the effect of mobility, channel model is modified. In path loss model, channel gain depends only on the distance as

\[
\Gamma_{mn} \propto \left( \frac{d_0}{d_{mn}} \right)^\gamma, \quad m \in \{S, R\} \quad n \in \{R, D_s, D_r\} \tag{5.9}
\]

where, \(d_{mn}\) is distance between \(m\) and \(n\).

To realize the effect of mobility, the model of (5.9) is modified as

\[
\Gamma_{mn} \propto \left( \frac{d_0}{d_{mn} + \theta} \right)^\gamma, \quad m \in \{S, R\} \quad n \in \{R, D_s, D_r\} \tag{5.10}
\]

where, \(\theta\) is random variable with zero mean and variance 10. The distance is assumed to be varied approximately +/- 10 units over the mean distance. Fig 5.8 and Fig 5.9 show the benefit of cooperation to source node in terms of higher data rate and energy saving considering the mobility of both the nodes for 100 random channel realizations. Even though the nodes are steady, wireless channel may face variation in channel gains. To realize the effect of time varying channel in path loss model, Rayleigh random variable with zero mean and different value of variances are added to channel gains between each node. Fig 5.10 and Fig 5.11 show the sustainability of cooperation even in time varying channel.

In Fig 5.8 and Fig 5.10, the dots show the direct data rate of source without cooperation. It is apparent that cooperation yields higher data rates compared to direct data rate even if the channel undergoes random variations for the value of \(\alpha\) between 0.4 and 0.7. Exchange of relay power and source bandwidth is able to withstand channel variations and ensures long lasting cooperation. When channel is favourable, the source continue cooperative mode and save energy. Fig 5.9 and Fig 5.11 demonstrate the energy saving by the source under random channel variations based on (5.7) and (5.8) Energy saving is positive for the value of \(\alpha\) between 0.4 and 0.7 in both the cases channel variations.
Fig 5.8 Source data rate with random variation in channel due to node movement

Fig 5.9 Source energy saving with random variation in channel due to node movement
Fig 5.10 Source data rate achieved with random channel variations

Fig 5.11 Source energy saving with random channel variation
In Fig 5.8 and Fig 5.10, the dots show the direct data rate of source without cooperation. It is apparent that cooperation yields higher data rates compared to direct data rate even if the channel undergoes random variations for the value of $\alpha$ between 0.4 and 0.7. Exchange of relay power and source bandwidth is able to withstand channel variations and ensures long lasting cooperation. When channel is favourable, the source continue cooperative mode and save energy. Fig 5.9 and Fig 5.11 demonstrate the energy saving by the source under random channel variations based on (5.7) and (5.8). Energy saving is positive for the value of $\alpha$ between 0.4 and 0.7 in both the cases of channel variations.

For ensuring long lasting cooperation and mutual benefit, matching of suitable source and relay is essential. In the next sub-section, iteration based conventional approach is discussed. A One-shot and accurate approach is also presented to make the match making process fast and low overhead.

### 5.4.5 Comparison with Other Exchange Techniques

Power-Bandwidth resource exchange techniques are found in (Simeone), (Toroujeni) and (D. R. Zhang). In Table 5.2, a comparison of the proposed exchange mechanism is done with these references. The mechanism in (Simeone), needs full channel state information. Moreover, many relays share the bandwidth of source for fraction of time. As a result, the relays cannot achieve higher data rate. In (Toroujeni), relay gets bandwidth for only fraction of time slot. The mechanism mentioned in (D. R. Zhang), source allocates a part of bandwidth to relay, in addition of the bandwidth possessed by the relay. Practically, it needs extra efforts to transmit in two different bands simultaneously. The proposed mechanism allocates a part of bandwidth for entire duration to the relay. It enables relay to utilize that part of the bandwidth as per its desire. The source restricts its transmission for fraction of the bandwidth for a fraction of time, which enable the source to save energy, in addition of getting higher data rate, by continuing resource exchange.
Table 5.2 Exchange mechanisms in literature

<table>
<thead>
<tr>
<th>Source transmission</th>
<th>Relay transmission</th>
<th>Limitation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>(Simeone)</strong></td>
<td>Whole bandwidth is used for fraction of time slot.</td>
<td>Remaining fraction of time slot is distributed among relays.</td>
</tr>
<tr>
<td><strong>(Toroujeni)</strong></td>
<td>Whole bandwidth is used for fraction of time slot.</td>
<td>For remaining time, the spectrum is shared between relay’s own transmission and source re-transmission</td>
</tr>
<tr>
<td><strong>(D. R. Zhang)</strong></td>
<td>Fraction of bandwidth is used for entire time slot.</td>
<td>Relay gets extra spectrum in addition to its own spectrum</td>
</tr>
<tr>
<td><strong>Proposed</strong></td>
<td>Fraction of bandwidth for fraction of time slot</td>
<td>Fraction of bandwidth for entire time slot</td>
</tr>
</tbody>
</table>

### 5.5 Source-Relay Negotiation Procedure

In self-configuring, distributed, multi-node scenario, the node searches for the suitable partner in the vicinity. Equilibrium of resource exchange depends on channel gains, available resource and target data rates of both the nodes. For discussing the negotiation procedure, the presence and readiness of the tentative partner are assumed. The node having bandwidth resource dominates the negotiation procedure by taking the initiative. The node acting as a source node proposes a fraction of the bandwidth to get relaying power offers from the relay nodes. The iterative procedure for step-by-step negotiation of resource exchange is presented in Fig 5.12. Source initiates by offering small fraction, say 0.1 of bandwidth.
Iterative negotiation procedure

Source announces small fraction of bandwidth $\Delta W$ at random, say 0.1

Start

No

Direct data rate $R_s^{NC}$ < target data rate $R_s^{tar}$?

Yes

Source announces small fraction of bandwidth $\Delta W$ at random, say 0.1

Relay offers relaying power $P_{RS}$ using (5.5) and (5.6)

Source increases $\Delta W$

Source increases $\Delta W$

Source continues to transmit non-cooperatively

Relay offers relaying power $P_{RS}$ using (5.5) and (5.6)

Source evaluates $R_s^C$ with $(W_{si}^{total} - \Delta W)$ and relaying power $P_{RS}$ using (5.2) and (5.3)

No

Yes

Current $R_s^C$ > $R_s^{NC}$?

No

Cooperative data rate $R_s^C$ ≤ target data rate $R_s^{tar}$?

Yes

Source confirms the amount of exchange and starts cooperative communication

End

Fig 5.12 Iterative negotiation procedure
Relay calculates the amount of power that can be spared at that bandwidth using (5.5) and (5.6). Source confirms quantity of resources exchanged, if it is acceptable to it. Otherwise, source offers more bandwidth to get more relaying power. Offering of larger fraction of bandwidth would not result in increased data rate as depicted in Fig 5.5. Then, source prefers to communicate non-cooperatively. The iterative negotiation procedure depicted in Fig 5.12 is time consuming and requires more overheads. A one-shot, accurate, and low overhead negotiation procedure is presented in Fig 5.13. In this approach, the node interested to become relay initiates the procedure by revealing its parameters in terms of 3-tuple \((R_{r}^{tar}, h^{Drr}, P_{R}^{total})\).

In this negotiation procedure, the relay reveals its parameters in terms of a tuple \((R_{r}^{tar}, h^{Drr}, P_{R}^{total})\) at the beginning of frame or at regular interval of time. To get the exchange deal done with the source, the relay has to reveal its true parameters. Otherwise, the relay would not get benefit of cooperation. For example, if the relay declares high target data rate \(R_{r}^{tar}\) in order to get more bandwidth from the source, the source would demand high relaying power in return. If the relay demands higher than the requirements, it may not be selected by any source.

After receiving relay parameters, the source calculates \(P_{RS}\) considering possible values of \(W_{r}\). \(P_{RS}\) can be calculated by re-arranging (5.5) and applying power budget as \(P_{R}^{total} \geq P_{RR} + P_{RS}\).

\[
P_{RS} = P_{R}^{total} - \frac{N_0}{|h^{Drr}|^2} \times \left(2^{\left(\frac{R_{r}^{tar}}{W_{r}}\right)} - 1\right) \tag{5.11}
\]

Source calculates required minimum of bandwidth \(W_{st}\) by inserting \(P_{RS}\) calculated in (5.11) in (5.4). Source also checks if available bandwidth is sufficient or not to cater the own requirement and relay’s requirements as \(W_{s}^{total} \geq W_{s} + W_{r}\). There may be more than one value of \((W_{r}, P_{RS})\) to ensure mutual benefit in cooperation. Then source has to select any one value of \((W_{r}, P_{RS})\). Suppose cooperation is possible for two values of \(W_{r} = W_{r1}\) and \(W_{r2}\) such that \(W_{r1} < W_{r2}\). The source may offer smaller bandwidth for keeping large portion for itself or offer larger bandwidth to get more relaying power and save own energy. The source confirms amount of exchanged resources and cooperative phase begins. This technique requires very less overhead to reach mutually acceptable deal. Also, it reaches the final deal in single shot. Both the node, need only local channel state information and simple computation. These features make the technique suitable for distributed network.
One-shot negotiation procedure

1. Start
2. Relay reveals parameters $R_{tar}^{t}, h^{drr}, P_{R}^{total}$
3. Source calculates $P_{RS}$ using (5.9) for different values of $W_{r}$.
4. Let $\Psi_{k}$ be a 2-tuple of possible values of $(W_{r}, P_{RS})$ within the constraint of maximum available resource $W_{s}^{total} \geq W_{s} + W_{r}$ and $P_{R}^{total} \geq P_{RR} + P_{RS}$.
5. Does any $(W_{r}, P_{RS})$ satisfy $R_{s}^{c} \geq R_{s}^{tar}$?
   - Yes: Source selects $(W_{r}, P_{RS})$, if more than one $(W_{r}, P_{RS})$ exists.
   - No: Source searches for another relay.
6. Source informs $(W_{r}, P_{RS})$ to the relay.
7. End

Fig 5.13 One-shot negotiation procedure
5.6 Conclusion

Cooperation stimulation and resource optimization framework for successful and long lasting cooperation has been presented in this chapter. The framework proposed here has proved that the nodes involved in cooperation by exchanging complementary resources can earn benefit and hence, tried to remain in cooperation. Source having sufficient bandwidth but less power cooperates with relay having sufficient power but no bandwidth and both of them have achieved their target data rates, which was impossible to achieve individually. When source target data rate is 1bit/unit, source offers bandwidth from 5.2 to 7.3 units in exchange of relay power from 1 to 4.5 units. When source target is 2 bits/unit, source keeps more bandwidth with it and offers bandwidth from 0.2 to 4.7 units in exchange of relay power from 1 to 4.5 units. Source can achieve the target for the range of $\alpha$ from 0.4 to 0.7, even if relay target changes from 0.8 to 1.2. It is demonstrated that source could save 21% to 71.5% energy by restricting transmission to only a part of its bandwidth and relay was able to achieve its target by getting the part of source’s spectrum. Robustness of this framework has been tested on 100 random channel variation and it has been found that cooperation with the same node remains unchanged and source has gained 13.4% to 46.7% more data rate compared to direct transmission. At the end, one-shot and accurate negotiation procedure has been discussed. It requires the three parameters from relay to establish cooperation. It also enforces relay to reveal the true parameters to enjoy mutual benefits.