Opportunistic routing and Cooperative Routing

Opportunistic routing is a new paradigm in routing for wireless sensor network which chooses the node closest to the target node for forwarding the data. It uses the broadcasting nature of wireless sensor networks. Opportunistic routing has increased the efficiency, throughput and reliability of sensor networks. Many energy saving techniques has been introduced using opportunistic routing in wireless sensor networks for increasing the network lifetime. In this lecture, we have elaborated the basic concept of Opportunistic routing, the first part of the lecture, different areas in which it has been claimed to be beneficial, some protocols their metrics and their drawbacks. The second part of the lecture will focus on cooperative routing

1. Introduction

Wireless sensor networks (WSNs) are the network of spatially distributed sensors which gathers information from the physical world. It is used for monitoring environmental factors like temperature, pressure moisture etc. and send this data to the sink or destination node. WSN has proven beneficial in number of applications in the area of traffic surveillance, military application, weather forecasting, landslide detection, fire detection etc. It is the backbone of the emerging technologies like Internet of Things (IoT), cyber physical system (CPS) etc. The most interesting contribution of WSN is in the healthcare. WSN in healthcare itself is the topic of research which has gained much popularity these days. The potential of sensing the information from the physical entities makes the wireless sensor network a hot topic for the research.

Routing is the difficult task in terms of wireless sensor network. Designing a routing protocol for wireless sensor network is different from designing it for the traditional networks. In case of the WSN, there is a strict energy saving requirement and there is a issue of the increasing network lifetime. Therefore, while designing the routing protocol for WSN resource management is important. The main function of the routing is route selection and data forwarding. The route selection includes selecting the best route between two nodes. The data transmission is done by selecting the next node or hop to forward the data. The packet forwarding in the traditional routing approaches for multihop wireless networks is done by selecting the node proactively at the sender side before transmission. Traditional multi-hop routing strategies suppresses the broadcasting nature of the wireless networks by using the Automatic Repeat Request [ARQ] or Forward Error Control [FEC] Data link techniques .

The new approach discussed in this article uses the broadcasting nature of the wireless network for packet forwarding. This approach is named as “Opportunistic Routing (OR)”. The key idea behind OR is to use the broadcasting nature of wireless network such that transmission from one node can be overheard by multiple nodes. Instead of choosing the next forwarder node ahead of time, the OR chooses the next node dynamically at the time of transmission. The forwarding is done by the node closest to the destination. It has been shown that OR gives better performance than traditional routing. The key task of the OR is to select the forwarder set and prioritize the nodes in the set. Consider the following example. Here the source node S has four intermediate nodes with packet delivery probability of 15%. Each intermediate node has packet delivery probability of 85% to the destination. Traditional routing will choose only one intermediate node for data forwarding, while OR will consider all these nodes for data forwarding. Thus, OR proves to be more efficient and reliable than traditional routing. In the remaining paper the existing work related to the OR in different types of networks and its comparative analysis

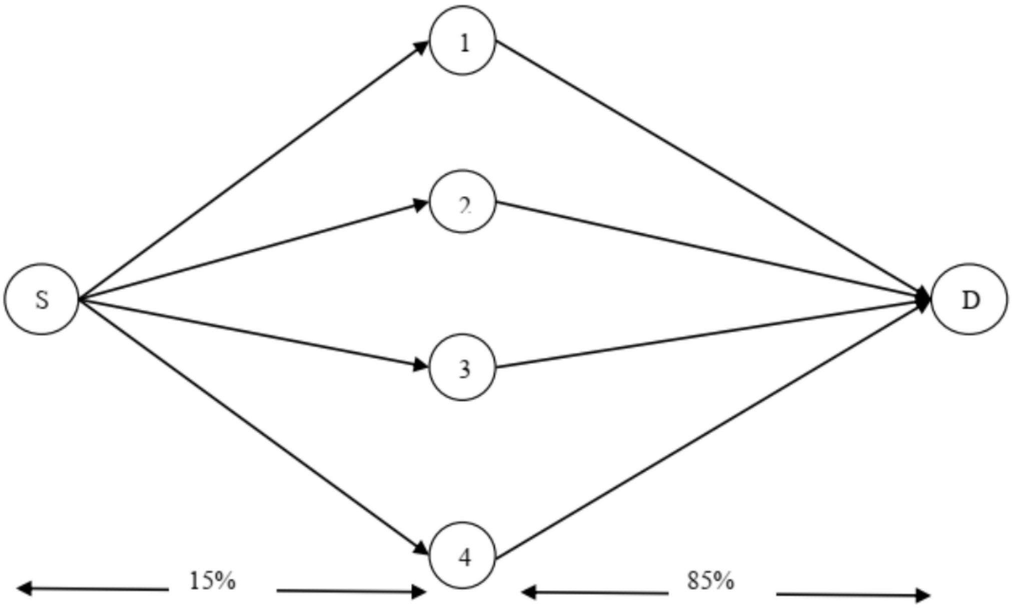

Fig. 1. Illustration in which each source node has multiple intermediate nodes along with packet delivery probability for data transmission to the destination node.

Geographic Random Forwarding (GeRaF) for Ad Hoc and Sensor Networks: Multihop Performance

Geographic Random Forwarding, is based on geographic routing. In wireless network the relay node is not known by the sender but is decided after the transmission. It uses the telecasting nature of the wireless network. Since the topologies are randomly changed, the sender node does not know which of its neighbouring node will act as a relay node. Hence, to deal with contention at the receiver end, author has proposed the above scheme. The basic idea of the paper is as follows: The sender node simply broadcasts the packet along with its own location and destination location. All the listening node in the neighbour will receive the packet and based on the own distance from the destination, they prioritize themselves to act as relay node. The relayed packet is then sent to a broadcasting address which also contains the transmitter and final destination location thus providing a geographic route without maintaining routing table.

The analysis of the multihop performance is done in terms of the number of hops to reach to the destination as a function of distance and the number of nodes in the neighbour nodes.

ExOR: Opportunistic Multi-Hop Routing for Wireless Networks

This is the first most basic protocol which practically implemented the Opportunistic Routing in the wireless networks. ExOR uses batches to send the packets. The source node collects the packets which are intended to the same destination and groups them into a batch. Each batch has its own Batch ID. The source node chooses the Batch ID and the forwarder list prioritized based on the ETX metrics[3]: shorter the distance of node from target node higher the priority. Only the nodes having higher priority are included in the forwarder list. Each node in the forwarder list maintains a local batch map. The node adds the packet into the packet buffer for the corresponding batch. The node compares the entry for each batch map in the packet with corresponding entry in the local batch map and if the higher priority entry is detected, it replaces the entry in the local batch map. ExOR implements scheduled transmission of packets to ensure that only one node sends the packet at one time.
The following example illustrates the working of ExOR.

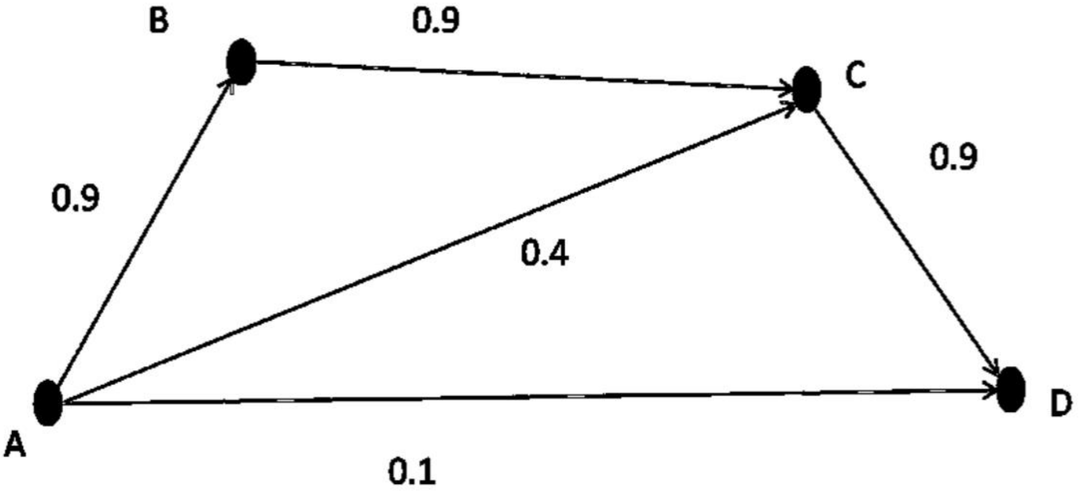

Fig. 2. Example of four node network with link delivery probabilities.

Suppose Node A wants to send the packet to node D, so for A, the list of forwarding nodes will be (D,C,B) Because EXOR tries to send the packet to the node which has least remaining distance from the destination. So if B, C, D receive the packet then each of them sends ACK to A along with their sender ID. If D is the first to send the ACK with its own ID as highest (as it is the first candidate in the forwarding list). So, if the C doesn't receive this ACK it sends its own ACK with own ID as the highest ID. At last B which has received the ACK sent by D, sends its own ACK with D as highest ACK. Thus C doesn't forwards the packet because it knows through B's ACK that The highest known ACK.

ExOR achieves higher throughput than the traditional routing but it has following drawbacks.
1.ExOR doesn't respond to the no updated measurements. It only considers the information available at the time of transmission. So, the incorrect measurements may degrade its performance and also may cause packet duplication.
2. It always seeks the coordination among all the nodes which causes overhead in case of large network. It doesn't reuse the information.

Optimal Forwarder List Selection in Opportunistic Routing

. The assumption made here is that the low priority nodes can always here the broadcast of the high priority node thus there will be no duplicate transmission of packets. Under this assumption the author proposes the Minimum Transmission Scheme algorithm, which computes the optimal forwarding list. While using this algorithm in ExOR instead of the ETX , the MTS based ExOR gives fewer transmissions than that of the ETX based ExOR. Thus the throughput of the MTS based ExOR is better than that of the ETX based ExOR. However in certain cases when the perfect ACK condition is not satisfied, the ETX based ExOR performs well than the MTS based ExOR.

Simple, Practical, and Effective Opportunistic Routing for Short-Haul Multi-Hop Wireless Networks

Here author proposes the effective opportunistic routing scheme for short haul multi-hop wireless networks . This modified Opportunistic routing algorithm implements the scheme of sending the ACK after receiving packet. In this algorithm the only the destination can opportunistically receive the packet by overhearing the transmission of the nodes in the traditional networks. After the destination node receives the packet from the priori node it sends the ACK to all the other nodes in the path. The node will only retransmit the packet in case it did not receive the packet from either destination or next node in the path. Hence, the destination node can easily discard any duplicate packets. Thus this algorithm reduces the packet duplication rate. Also it increases the throughput than that of other opportunistic algorithms. It is simple and can be integrated with the other Opportunistic algorithm.

Spectrum Aware Opportunistic Routing in Cognitive Radio Networks

Shih-Chun Lin and Kwang-Cheng Chen proposes the SAOR i.e. Spectrum Aware Opportunistic Routing for Cognitive Radio Network (CRN). The algorithm proposed by the authors uses the optimal link transmission (OLT) as a cost metric for prioritizing the nodes in the forwarded list. The OLT metric is considered in the delay aspect. Two more metrics namely optimal path metric and node metrics further elaborates the number of hops in the path and the delay status within each path respectively to the destination.

Due these metrics SAOR gives QoS guarantees like better throughput and improved end to end delay performances than the traditional routing algorithms for CN.

Energy-Efficient Opportunistic Routing in Wireless Sensor Networks

This proposes the scheme to choose the forwarding list using the cost metric of minimum energy depletion while broadcasting in the wireless sensor network. Energy Efficient Opportunistic Routing (EEOR) calculates the expected cost for each node to forward the data and then selects the forwarding list. The basis of selecting forwarding list is that the expected cost of the node to be added must be less than the prefix forwarding list so that the total expected cost of the new forwarding list will be minimum. The expected cost updating of each node is done by the algorithm similar to the Bellman Ford algorithm.

EEOR consumes less time than that of ExOR for both transmission and receiving data. Due to the cost metrics considered in EEOR, the average size of the forwarding list of the EEOR is much less than that of the ExOR . In case of the total energy consumption, EEOR performs better than EXOR . Comparing both the protocols for the packet loss rate and end to end delay EEOR performs better than ExOR .

A theoretical model for opportunistic routing in ad hoc networks

It considers delivery ratios and the priority order among the nodes to select the next hop for the packet forwarding. It focuses on giving a closed form expression for average transmission number. This model helps to analyze the performance parameters such as packet dropping rate, packet transmission number, end to end packet delay etc.

A Trusted Opportunistic Routing Algorithm for Vanet

It describes the trade-off between the cost metric and security factor. The author proposes the algorithm which calculates the degree of trust and updates the direct trust degree. The degree of trust is based on the direct observation of the neighbouring nodes while indirect trust degree is based on the recommendation. By using these factors the author has implemented the Trust Opportunity Forwarding Mechanism using cost effective forwarding list and has prioritize each node in the list by its cost distance from destination.

The TMCOR algorithm performs well in all three metrics viz. throughput, end to end packet delay and security gains. TMCOR prohibits the malicious node to participate in the network by judging them in terms of trust degree. Thus, reducing End to End packet delay and increasing security gains.

A Novel Socially-Aware Opportunistic Routing Algorithm in Mobile Social Networks

The proposed distributed protocol is Social Relation Opportunistic Routing (SROR) to compute best forwarding node in routing. The protocol mainly considers the social relations, mobility patterns and social profiles for Mobile Adhoc Networks (MANETs). For selection of the forwarding node in the routing SROR following three matching parameters are taken into account viz. social profile matching, social connectivity matching and social interaction. Hence when the node wants to send the packet, due to the algorithm there is high possibility that the best candidates sharing similar interest tend to meet again to forward the data. SROR gives high packet delivery rate and routing efficiency compared to other protocols for MANETs.

Opportunistic Routing Algorithm for Relay Node Selection in Wireless Sensor Networks

mainly concerns about the energy savings concept in the WSNs. It describes the algorithm which focuses on minimizing the energy consumption of the network. The author proposes Energy Saving via Opportunistic Routing (ENS-OR). The algorithm implements the concept of energy efficient node (EEN) which happens to be a virtual relay node obtained by relay function on several real nodes based on their residual energy. The forwarder list selection and prioritizing the nodes in the that list is carried out by the ENS-OR algorithm calculates the optimal hop distance to calculate the next hop node to forward the data. The nodes in the forwarding list prioritize themselves by their residual energy and their distance from EEN.

ENS-OR obtains better network energy usage. Also it increases the network lifetime by achieving higher residual energy of the nodes in the network. The packet delivery rate of ENS-OR is greater than that of GeRaF .

CONCLUSION AND FUTURE DIRECTIONS

Opportunistic routing in WSN has attracted many researchers these days. Since OR utilizes the broadcasting nature of wireless networks it has been proven to be more efficient than the traditional routing approach foe WSN. The WSNs have many issues such as lack of a predetermined infrastructure of networks, limited battery power of sensor nodes, disastrous environmental conditions to which sensors are vulnerable etc. Resource allocation becomes the critical issue when it comes to sensor networks, since it has limited battery power. OR overcomes many of these issues regarding WSNs. It gives better utilization than traditional approach. The existing protocols based on OR have mainly focused on the Energy saving, reducing data redundancy, increasing the utilization etc. ExOR is a first to implement OR in WSN, it improves the efficiency of routing but it has the problem of packet duplication which is further reduced in MTS . OR also helps in protocol design for VANETs, MANETs and CRN which provides QoS guarantees and better throughputs.

In terms of future scope, OR has to improve in terms of energy saving techniques. Since, sensor nodes tends to deplete their energy fast, the energy saving becomes the prime issue for sensor networks. OR integrated with duty cycle assignment can prove efficient in terms of energy savings. Since all nodes in the networks need not be active all the time the nodes which are not supposed to take part in the transmission and receiving activities can be pushed to sleep mode. This mechanism can help to improve network lifetime.

Cooperative Routing in Wireless Networks

The joint problem of transmission-side diversity and routing in wireless networks is studied. It is assumed that each node in the network is equipped with a single omni-directional antenna and multiple nodes are allowed to coordinate their transmissions to achieve transmission-side diversity. The problem of finding the minimum energy route under this setting is formulated. Analytical asymptotic results are obtained for lower bounds on the resulting energy savings for both a regular line network topology and a grid network topology. For a regular line topology, it is possible to achieve energy savings of 39%. For a grid topology, it is possible to achieve energy savings of 56%. For arbitrary networks, we develop heuristics with polynomial complexity which result in average energy savings of 30% – 50% on simulations.

Introduction

we study the joint problem of route selection and physical layer space diversity in ad-hoc wireless networks for the sake of energy efficiency. It is known that in an ad-hoc network, nodes usually spend most of their energy in communication For this reason, the problem of energy efficiency and energy efficient communication in wireless networks has received a lot of attention. This problem, however, can be approached from two different angles: energy-efficient route selection algorithms at the network layer or efficient communication schemes at the physical layer. A combined cross-layer approach, that designs the network layer protocols to exploit the special properties of the wireless physical layer, may be beneficial in wireless networks.

Multi-path fading is one of the fundamental limiting factors in wireless communication, resulting in a higher likelihood of transmission errors than in a wired medium. Equalization, channel coding, and diversity are three techniques that are generally used, independently or in tandem, to improve the wireless link quality . In diversity techniques, information is transmitted over channels that are affected by uncorrelated fading and noise processes. This effect may be achieved by separating the channels in frequency, time, or space. These techniques are reviewed in detail in . Space diversity is usually achieved by employing multiple transmitting and/or multiple receiving antennas. Multiple antennas, on the transmitter or on the receiver side, must be about 0.4λ apart, a few inches at the typical carrier frequencies, to achieve the desired effect of uncorrelated channels However, in some cases, the use of multiple transmitters or receivers may be impractical, infeasible, or too costly. In this paper we propose a new way of achieving space diversity by allowing cooperation among nodes for routing purposes, in effect creating a virtual antenna array. The following simple example best illustrates the potential benefits of this approach.

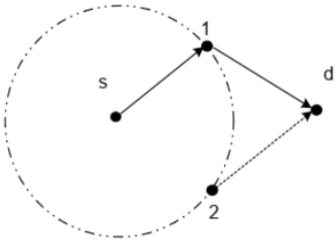

Figure 1: Cooperative Routing

Figure 1 depicts a simple 4-node wireless network, where s and d are the source and the destination nodes, respectively. We assume that the minimum energy path from s to d is through node 1, i.e. $s \rightarrow 1 \rightarrow d$. In this case, node 2, which is also located within the transmission radius of s to 1, receives the information transmitted from s at no additional cost. This property of wireless medium is usually referred to as *Wireless Broadcast Advantage* (WBA) . Cooperation between nodes 1 and 2 in the second hop will create transmission-side diversity and may result in a lower energy route from s to d. Under this setting, each node can participate in cooperative transmission after it has completely received the information. For this reason, the problem of finding the optimal path is a multi-stage decision making problem, where at each stage a set of nodes may cooperate to relay the information to a chosen node. Thus the minimum energy cooperative route may be viewed as a sequence of sets of cooperating nodes along with an appropriate allocation of transmission powers. The tradeoff is between spending more energy in each transmission slot to reach a larger set of nodes, and the potential savings in energy in subsequent transmission slots due to cooperation.

Consider a wireless ad-hoc network consisting of arbitrarily distributed nodes where each node has a single omni-directional antenna. We assume that each node can dynamically adjust its transmitted power and phase to control its transmission range and possibly synchronize with other nodes. Based on these two assumptions, The information is routed from the source node to the destination node during a sequence of transmission slots, where each transmission slot corresponds to one use of the wireless medium. In each transmission slot/stage, a node or group of nodes is selected to transmit the information to another single node (broadcast mode) or another group of nodes (cooperation mode). The routing problem can be viewed then as a multi-stage decision problem, where at each stage the decision is to pick the set of nodes S participating in relaying the information and the set of nodes T receiving the information. The objective is to get the information to the destination with minimum energy. The set of nodes that have the information at the k^{th} stage is referred to as the k^{th}-stage *Reliable Set*, S_k, and the routing solution may be expressed as a sequence of expanding reliable sets that starts with only the source node and terminates as soon as the reliable set contains the destination node. The single-stage cost, referred to as the Link Cost between S and T, $LC(S,T)$, is the minimum power needed for transmitting from S to T.

The wireless channel between any transmitting node labeled s_i and any receiving node labeled t_j is modeled by two parameters, its magnitude attenuation factor α_{ij} and its phase delay θ_{ij}. We assume that the channel parameters are estimated by the receiver and fed back to the transmitter. This assumption is reasonable for slowly varying channels, where the channel coherence time is much longer than the block transmission time. We also assume a free space propagation model where the power attenuation α_{ij}^2 is proportional to the inverse of the square of the distance between the communicating nodes s_i and t_j. For the receiver model, we assume that the desired minimum transmission rate at the physical layer is fixed and nodes can only decode based on the signal energy collected in a single channel use. We also assume that the received information can be decoded with no errors if the received SNR level is above a minimum threshold SNR_{min}, and that no information is received otherwise. Without loss of generality, we assume that the information is encoded in a signal ϕ that has unit power $P_\phi = 1$ and that we are able to control the phase and magnitude of the signal arbitrarily by multiplying it by a complex scaling factor w_i before transmission. The noise at the receiver is assumed to be additive, and the noise signal and power are denoted by $\eta(t)$ and P_η respectively. This simple model allows us to find analytical results for achievable energy savings in some simple network topologies.

Link Cost Formulation

In this section, our objective is to understand the basic problem of optimal power allocation required for successful transmission of the same information from a set of source nodes $S = \{s_1, s_2, \cdots, s_n\}$ to a set of target nodes $T = \{t_1, t_2, \cdots, t_m\}$. In order to derive expressions for the link costs, we consider 4 distinct cases:

1. *Point-to-Point Link:* $n = 1, m = 1$: In this case, only one node is transmitting within a time slot to a single target node.

2. *Point-to-Multi-Point, Broadcast Link:* $n = 1, m > 1$: This is the broadcast mode, where a single node is transmitting to multiple target nodes.

3. *Multi-Point-to-Point, Cooperative Link:* $n > 1, m = 1$: This is the cooperative mode, where multiple nodes cooperate to transmit the same signal to a single node. We will assume that coherent reception, i.e. the transmitters are able to adjust their phases so that all signals arrive in phase at the receiver. In this case, the signals simply add up at the receiver and complete decoding as long as the received SNR is above the minimum threshold SNR_{min}. In this paper, we do not address the feasibility of precise phase synchronization. The reader is referred to [12] for a discussion of mechanisms for achieving this level of synchronization.

4. *Multi-Point-to-Multi-Point Link:* $n > 1, m > 1$: This is not a valid option under our assumptions, as synchronizing transmissions for coherent reception at multiple receivers is not feasible. Therefore, we will not be considering this case.

Point-to-Point Link: $n = 1, m = 1$

In this case, $S = \{s_1\}$ and $T = \{t_1\}$. The channel parameters may be simply denoted by α and θ, and the transmitted signal is controlled through the scaling factor w. The model assumptions made in Section 2 imply that the received signal is simply

$$r(t) = \alpha e^{j\theta} w \phi(t) + \eta(t).$$

The total transmitted power is $P_T = |w|^2$. Therefore the SNR at the receiver is $\frac{\alpha^2 |w|^2}{P_\eta}$. For complete decoding at the receiver, the SNR must be above the threshold value SNR_{min}. Therefore the minimum power required $\hat{P_T}$, and hence the point-to-point link cost $LC(s_1, t_1)$, is given by

$$LC(s_1, t_1) \equiv \hat{P_T} = \frac{SNR_{min} P_\eta}{\alpha^2} \tag{1}$$

In equation 1, the point-to-point link cost is proportional to $\frac{1}{\alpha^2}$, which is the power attenuation in the wireless channel between s_1 and t_1, and therefore is proportional to the square of the distance between s_1 and t_1 under our propagation model.

Point-to-Multi-Point, Broadcast Link: $n = 1, m > 1$

In this case, $S = \{s_1\}$ and $T = \{t_1, t_2, \cdots, t_m\}$, hence m simultaneous SNR constraints must be satisfied at the receiver. Assuming that omni-directional antennas are being used, the signal transmitted by the single node s_1 is received by all nodes within the transmission radius. Hence, a broadcast link can be treated as a set of point-to-point links and the cost of reaching a set of node is the maximum over the costs for reaching each of the nodes in the target set. Thus the minimum power required for the broadcast transmission, denoted by $LC(s_1, T)$, is given by

$$LC(s,T) = max\{LC(s_1 t_1), LC(s_1 t_2), \cdots, LC(s_1 t_n)\} \tag{2}$$

Multi-Point-to-Point, Cooperative Link: $n > 1, m = 1$

In this case $S = \{s_1, s_2, \cdots, s_n\}$ and $T = \{t_1\}$. We assume that the n transmitters are able to adjust their phases in such a way that the signal at the receiver is

$$r(t) = \sum_{i}^{n} \alpha_{i1} |w_i| \phi(t) + \eta(t).$$

The power allocation problem for this case is simply

$$\text{Minimize} \qquad \sum_{i=1}^{n} |w_i|^2 \qquad\qquad \text{Subject to} \qquad \frac{|\sum_{i=1}^{n} w_i \alpha_{i1}|^2}{P_\eta} \geq SNR_{min} \tag{3}$$

Lagrangian multiplier techniques may be used to solve the constrained optimization problem above, and the resulting optimal allocation for each node i is given by

$$|\hat{w}_i| = \frac{\alpha_{i1}}{\sum_{i}^{n} \alpha_{i1}^2} \sqrt{SNR_{min} P_\eta} \tag{4}$$

The resulting cooperative link cost $LC(S, t_1)$, defined as the optimal total power, is therefore given by

$$LC(S, t_1) \equiv \hat{P}_T = \frac{1}{\sum_{i=1}^{n} \frac{\alpha_{i1}^2}{SNR_{min} P_\eta}} \tag{5}$$

It is easy to see that it can be written in terms of the point-to-point link costs between all the source nodes and the target nodes (see Equation 1) as follows:

$$LC(S, t_1) = \frac{1}{\frac{1}{LC(s_1,t_1)} + \frac{1}{LC(s_2,t_2)} + \cdots + \frac{1}{LC(s_n,t_1)}} \tag{6}$$

Minimum Cost Cooperative Route

The problem of finding the optimal cooperative route from the source node s to the destination node d formulated can be mapped to a Dynamic Programming (DP) problem. The state of the system at stage k is the reliable set S_k, i.e. the set of nodes that have completely received the information by the k^{th} transmission slot. The initial state S_0 is simply $\{s\}$, and the termination states are all sets that contain d. The decision variable at the k^{th} stage is U_k, the set of nodes that will be added to the reliable set in the next transmission slot. The dynamical system evolves as follows:

$$S_{k+1} = S_k \cup U_k \quad k = 1, 2, \cdots \tag{7}$$

The objective is to find a sequence $\{U_k\}$ or alternatively $\{S_k\}$ so as to minimize the total transmitted power P_T, where

$$P_T = \sum_k LC(S_k, S_{k+1} - S_k) \tag{8}$$

We will refer to the solution to this problem as the optimal transmission policy. This is a shortest path problem over a graph whose nodes are all the possible states and with arcs representing the possible transitions between states. As the network nodes are allowed only to either fully cooperate or broadcast, the graph has a special layered structure as

illustrated by Figure 3. Arcs between nodes in adjacent layers correspond to cooperative links, whereas broadcast links are shown by cross layer arcs. The costs on the arcs are the link costs defined. All terminal states are connected to a single artificial terminal state, denoted by D, by a zero-cost arc. The optimal transmission policy is basically the shortest path between nodes s and D. There are 2^n nodes in the graph for a network with $n+1$ nodes. Therefore standard shortest path algorithms will in general have a complexity of $O(2^{2n})$. We are able to take advantage of the special structure of this graph to come up with an algorithm with complexity reduced to $O(n2^n)$. However, the complexity is still exponential, which makes finding the optimal cooperative policy computationally intractable for large networks. For this reason, for arbitrary networks we will focus on developing computationally simpler and relatively efficient heuristics and on assessing their performance through simulation.

Simple Example

Having developed the necessary mathematical tools, we now present a simple example that illustrates the benefit of cooperative routing. Figure 2 shows a simple network with 4 nodes. The arcs represent links and the arc labels are point-to-point link costs. The diagrams below show the six possible routes, P_0 through P_5. P_0 corresponds to a simple 2-hop, non-cooperative minimum energy path between s and d. P_1, P_2, and P_3 are 2-hop cooperative routes, whereas P_4 and P_5 are 3-hop cooperative routes. Table 1 lists the costs of the six policies. The policy with the lowest cost is P_3, where nodes 1 and 2 receive the information in the first transmission slot due to the *Wireless Broadcast Advantage*, and nodes $s, 1, 2$ cooperate to transmit the information to d with minimum energy.

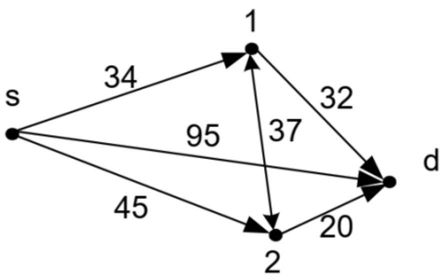

Figure 2: 4-Node Network Example

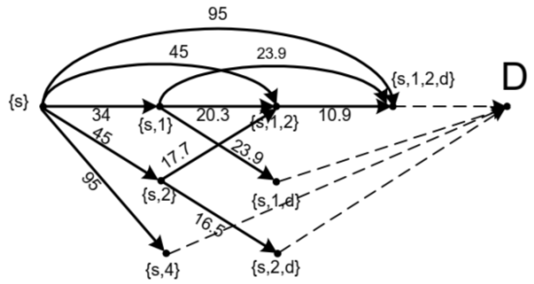

Figure 3: 4-Node Cooperation Graph

No.	Policy	Cost
P_0	$NonCooperative$	65
P_1	$(\{s\},\{s,2\},\{s,2,d\})$	≈ 61.5
P_2	$(\{s\},\{s,1\},\{s,1,d\})$	≈ 57.9
P_3	$(\{s\},\{s,1,2\},\{s,1,2,d\})$	≈ 55.9
P_4	$(\{s\},\{s,2\},\{s,1,2\},\{s,1,2,d\})$	≈ 73.6
P_5	$(\{s\},\{s,1\},\{s,1,2\},\{s,1,2,d\})$	≈ 65.2

Table 1: Transmission Policies for Figure 2

REFERENCE

1. Wireless Networking in the Developing World: A practical guide to planning and building low-cost telecommunications infrastructure (PDF) (2nd ed.). Hacker Friendly LLC. 2007. p. 425.

2. Pahlavan, Kaveh; Levesque, Allen H (1995). Wireless Information Networks. John Wiley & Sons. ISBN 0-471-10607-0.

3. Geier, Jim (2001). Wireless LANs. Sams. ISBN 0-672-32058-4.

4. Goldsmith, Andrea (2005). Wireless Communications. Cambridge University Press. ISBN 0-521-83716-2.

5. Molisch, Andreas (2005). Wireless Communications. Wiley-IEEE Press. ISBN 0-470-84888-X.

6. Pahlavan, Kaveh; Krishnamurthy, Prashant (2002). Principles of Wireless Networks – a Unified Approach. Prentice Hall. ISBN 0-13-093003-2.

7. Rappaport, Theodore (2002). Wireless Communications: Principles and Practice. Prentice Hall. ISBN 0-13-042232-0.

8. Rhoton, John (2001). The Wireless Internet Explained. Digital Press. ISBN 1-55558-257-5.

9. Tse, David; Viswanath, Pramod (2005). Fundamentals of Wireless Communication. Cambridge University Press. ISBN 0-521-84527-0.

10. Pahlavan, Kaveh; Krishnamurthy, Prashant (2009). Networking Fundamentals – Wide, Local and Personal Area Communications. Wiley. ISBN 978-0-470-99290-6.

11. Cognitive Ubiquitous Computing by Kwang-Cheng Chen, Feng-Seng Chu, Shin-Ming Cheng, Sheng-Yuan Tu, Shih-Chun Lin,Yu-Yu Lin, Po-Yao Huang and Ao Weng Chon