# PERFORMANCE ANALYSIS OF A POWER AWARE ROUTING PROTOCOL FOR AD HOC NETWORKS

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# Abstract

PERFORMANCE ANALYSIS OF A POWER AWARE ROUTING
PROTOCOL FOR AD HOC NETWORKS

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In this thesis, performance of the Contribution Reward Routing Protocol with Shapley Value (CAP-SV), a power-aware routing protocol for ad hoc networking is analyzed.

Literature study on ad hoc network routing and power-awareness is given. The overhead induced by the extra packets of the redirection mechanism of CAP-SV is formulized and the factors affecting this overhead are discussed. Then, the power consumption of CAP-SV is analytically analized using a linear power consumption model. It is shown that CAP-SV performs better than AODV regarding power consumption. The analysis validates the simulation results reported in the literature and provides general principles of how protocol and scenario parameters affect the performance.

**Keywords:** ad hoc networks, power-aware routing, CAP-SV protocol, performance analysis

# Öz

## TASARSIZ AĞLAR İÇİN GÜÇ-BİLİNÇLİ BİR YÖNLENDİRME PROTOKOLÜNÜN BAŞARIM İNCELEMESİ

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Bu tezde, tasarsız ağlar için güç bilinçli bir yönlendirme protokolü olan Katılım Ödüllendirme Protokol'ünün (CAP-SV) başarımı incelenmiştir.

Tasarsız ağlar ve güç-bilinçlilik konularının literatür araştırması verilmektedir. CAP-SV protokolünün yeniden-yönleme mekanizmasının ortaya çıkardığı fazlalık paketlerin doğurduğu yük formüllendirilmiş, ve bunu etkileyen etkenler tartışılmıştır. Daha sonra, CAP-SV'nin güç tüketimi, doğrusal güç tüketimi modeli esas alınarak analitik olarak incelenmiştir. Güç tüketimi göz önüne alındığında, CAP-SV'nin AODV'den daha iyi bir başarım sergilediği gösterilmiştir. Bu inceleme, gerek literatürde bildirilen benzetim sonuçlarını doğrulamakta, gerekse protokol ve senaryo değişkenlerinin başarım üzerindeki etkilerine dair genel prensipler ortaya koymaktadır.

**Anahtar Kelimeler:** tasarsız ağlar, güç-bilinçli yönlendirme, CAP-SV protokolü, başarım incelemesi

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**CHAPTERS**

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# List of Abbreviations

| | |
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| ABR | Associativity-Based Routing |
| AODV | Ad Hoc On Demand Distance Vector Routing |
| BEB | Binary Exponential Backoff |
| BER | Bit Error Rate |
| BROADEN | Binary Countdown/RTS/OTS/ATS/DTS/ETS/NTS |
| CAP-SV | Contribution Reward Routing with Shapley Value |
| CBR | Constant Bit Rate |
| CGSR | Cluster Gateway Switch Routing |
| CSMA-CA | Collision Sense Multiple Access with Collision Avoidance |
| CTS | Clear to Send |
| DBTMA | Dual Busy Tone Multiple Access |
| DCF | Distributed Coordination Function |
| DSDV | Destination Sequenced Distance Vector Routing |
| DSR | Dynamic Source Routing |
| DUCHA | Dual Channel MAC Protocol |
| FSR | Fisheye State Routing |
| GPS | Global Positioning System |
| IEEE | Institute of Electrical and Electronics Engineers |

| | |
|---|---|
| JMAC | Jamming-based Multiple Access Control |
| LAR | Location Aided Routing |
| LARRLM | Location Aware Routing with Reduced Location Maintenance |
| LORA | Least Overhead Routing Approach |
| MAC | Medium Access Control |
| MACA | Multiple Access with Collision Avoidance |
| MACA-BI | Multiple Access with Collision Avoidance by Invitation |
| MACAW | Multiple Access with Collision Avoidance for Wireless |
| MANET | Mobile Ad Hoc Network |
| MARCH | Media Access with Reduced Handshake |
| ORA | Optimal Routing Approach |
| PAMAS | Power Aware Multiple Access with Signaling |
| PAR | Power Aware Routing |
| QoS | Quality of Service |
| RDMAR | Relative Distance Microdiversity Routing |
| RO | Redirection Overhead |
| RRDR | Route Redirect |
| RREP | Route Reply |
| RREQ | Route Request |
| RTR | Ready to Receive |
| RTS | Request to Send |
| SSR | Signal Stability Routing |
| STAR | Source Tree Adaptive Routing |
| TEAM | Transmission Power Recursive Auction Mechanism |
| TORA | Temporally Ordered Routing Algorithm |
| WRP | Wireless Routing Protocol |
| ZHLS | Zone-Based Hierarchical Link State Routing |
| ZRP | Zone Routing Protocol |

# Chapter 1

# Introduction

Mobile ad hoc networks are computer networks that are set up by wireless nodes that are not interconnected by a fixed infrastructure. If a node needs to communicate with a node that is not inside its radio range, intermediate nodes are used as routers. Ad hoc networks are used in military applications, sensor networks, vehicular communications and personal area communications.

Since ad hoc networks consist of mobile nodes that run on limited battery power, protocols for ad hoc networking should be power efficient. The main objective of power-aware protocols is to maximize the time before the network partitions because of a node depleting its battery. For this purpose, power management methods are used at physical, medium access control and network layers.

At the physical layer, adaptive transmission power is used to avoid unnecessary power consumption. The main power consumption factor of a mobile node is the transmission/reception of a signal. So, at MAC and network layers, number of control packets is minimized. Retransmissons due to collision and erroneous transmissions should also be minimized. Idle nodes turn off their transceivers since they consume power even if they are not transmitting or receiving.

Contribution Reward Routing Protocol with Shapley Value (CAP-SV) is a power-aware routing protocol for ad hoc networks. The main idea behind CAP-SV is to redirect a route when redirecting leads to a less power-consuming path. CAP-SV employs game theory to award redirector nodes and stimulate cooperation. Also, the protocol uses a virtual currency system. A node with a high amount of virtual money means that the node has participated in a high number of communication sessions, and hence has got less amount of power. In this case, a wealthy node goes to sleep for a certain period of time in order to minimize the variance in power levels.

The objective of this study is to investigate power-management and efficiency in ad hoc routing. The performance of CAP-SV, a power-aware routing protocol for ad hoc networks is analyzed in terms of overhead due to extra messaging and power gain. The performance of CAP-SV under constant uniform traffic without mobility is studied in [10]. Their results are compared to the results obtained analytically.

The rest of this thesis is organized as follows: In Chapter 2, a survey of the relevant literature is given. Chapter 3 explains the performance analysis of CAP-SV in detail and presents the results of the analysis. Chapter 4 concludes with the summary of the analysis and by guidelines for the future work.

# Chapter 2

# Literature Survey

## 2.1 Wireless Ad Hoc Networks

The term *ad hoc* refers to “improvisioned, without preparation”. Similarly, an ad hoc network is a network that is set up spontaneously by a bunch of computing devices usually using wireless connections. The devices participating in the network can unexpectedly move out or new ones may enter. To make a concrete and a more rigorous definition, ad hoc networks are networks in which nodes distributedly perform the control operations due to the lack of dedicated infrastructure and central control. This situation leaves the burden of control tasks into the hands of each and every node in the ad hoc network. Therefore, every host has to act as terminals as well as routers in a distributed fashion [45]. As a more formal relation, an ad hoc network is a multi hop packet radio network [26].

The idea of ad hoc networking is a result of the need for a technique to set up a communications network without a backbone which demands deployment and maintenance. Ad hoc networks are widely used in military applications. Other applications include sensor networks which can be used for meteorological purposes or in disaster areas, and nomadic computing such as temporal conference networking, business networks, Bluetooth [7, 8] and vehicular communications.

The main properties of ad hoc networks are the wireless medium and mobility. Other important issues include heterogeneity, scalability, distributedness, security and power–awareness. Clustering [51] may be used to cope with scalability. Power–awareness will be studied extensively in the rest of this thesis.

### 2.1.1 Medium Access Control Methods in Ad Hoc Networks

Medium access control (MAC) is a serious problem in ad hoc networks. Since ad hoc networks are wireless and mobile networks, their MAC protocols need more sophisticated methods in order to solve issues like the hidden terminal andthe exposed node problems [43].

The IEEE 802.11 protocol [1, 2, 6] is widely used in ad hoc networks. It is based on carrier sense multiple access (CSMA) technique with additional collision avoidance (CA) feature. When a node has data to transmit, it first senses the medium. If it finds the medium idle, the node waits for a random back off period as a result of the CA feature. During this period, if the channel becomes busy, the node freezes its counter until the medium becomes idle again. When the counter runs out, RTS/CTS handshake takes place followed by data transmission. However, 802.11 was proposed for fully connected wireless networks and does not perform well in multi hop ad hoc networks [48].

There are other MAC protocols such as Multiple Access with Collision Avoidance (MACA) [23], MACA for Wireless (MACAW) [5], Multiple Access with Collision Avoidance - By Invitation (MACA-BI) [42], Power Aware Multi-Access Protocol with Signaling (PA-MAS) [40], Dual Busy Tone Multiple Access (DBTMA) [19, 20], Media Access with Reduced Handshake (MARCH) [46], Jamming-Based MAC (JMAC) [49], Binary Countdown/RTS/OTS/ATS/DTS/ETS/NTS (BROADEN) [50] and Dual-Channel MAC Protocol (DUCHA) [52]. These methods use a wide variety of methods including RTS/CTS mechanism, request–to–receive (RTR) packets, extra signaling, channel jamming, busy tone, and separating control and data channels.

### 2.1.2 Routing Techniques in Ad Hoc Networks

Some basic properties of ad hoc networks make the routing process very difficult. For instance, due to the limited power sources and bandwidth, routing should avoid unnecessary control signaling. Also, the medium has a high bit error rate (BER). Therefore, naturally, some packets will be resent reducing both the energies of the nodes and the throughput. This is another reason for the routing protocol to be efficient in terms of throughput.

The routing approaches for ad hoc networks can be investigated in three categories: table-driven (proactive), source initiated (reactive, on–demand) and hybrid protocols. In table-driven methods, each node keeps tables that keep information on the distance of each node, and the route to that node. These tables are updated periodically. In source initiated protocols, a route is found only when needed. Hybrid protocols divide the whole network into partitions. Within the partitions, proactive routing is used. Reactive protocols are employed when inter-partition communications are needed.

#### Proactive Routing Protocols

*Destination Sequenced Distance Vector (DSDV)*: DSDV [35] finds the routes based on Bellman-Ford's shortest path algorithm. Routing table updates are sent periodically. There are two types of update packets. One is the incremental packet which includes relatively smaller changes in the topology. The other is the full dump which conveys the overall topology information. Full dump packet is sent infrequently in order not to reduce the channel utilization. Each route is sent along with a sequence number. A node receiving an update packet checks the new metric and the new sequence number. The node changes its table if the sequence number is larger, or the sequence number is the same but the metric is better. The sequence numbers are generated by the destination of a path, or an intermediate node that has detected a broken link. New routes are not advertised immediately in order to prevent fluctuations. Rather, they are sent when a stability timer (which is dynamically updated) runs out. The broken links are an exception. When a node finds out that a breakage has occurred, it instantly broadcasts this information.

*Wireless Routing Protocol (WRP)*: This protocol [32] also uses a path finding algorithm which overcomes the count-to-infinity problem [43]. The nodes learn about their neighbors by listening to the medium. As a consequence, if a node does not transmit anything for a certain period of time, it needs to send out a “hello packet” to declare its presence. Each node maintains four tables. Distance table stores the distance of each node. Routing table gives the next hop for a given destination. Link-cost table keeps the cost of the links, which may be hop count or delay. Finally, message retransmission list holds the sequence number of the update message, a retransmission counter and the list of the neighbors that have to acknowledge the update message.

*Clusterhead Gateway Switch Routing (CGSR)*: Nodes are divided into clusters, each having a cluster head. The algorithm uses a distributed cluster head selection algorithm. The route used in this protocol is from the source to its cluster head, then to a gateway node, then to the destinations cluster head, and finally to the destination node. Each node keeps a “cluster member table” to store destination cluster heads for each host. These tables are broadcast periodically using the DSDV protocol. When a cluster head moves away from its cluster, a new one must be elected. Least cluster change principal is used in this process. [12]

*Source Tree Adaptive Routing (STAR)*: STAR [17] differs from other routing protocols by its “least overhead routing approach (LORA)” rather than the classic “optimum routing approach (ORA)”. It reduces the control overhead by using the already found routes even if they are not optimal as long as they are valid. STAR maintains path information for only the active routes, i.e. the ones in use. “Source tree” means the set of links a node uses in its preferred path to a destination. In cases of unreachable destinations, new destinations, possible permanent routing loops and the cost of paths exceeding their initial values by a threshold, a node reports updates to its source tree. Since each packet contains the source tree it is traversing, it is easy to detect loops. In case of a loop, the packet is discarded and a ROUTE-REPAIR update message is sent back to the loop. Update packets are time-stamped for the purpose of validation, but routes do not age out with time as long as they are operating; therefore periodic updates are unnecessary. This property greatly reduces the number of update packets generated. It is reported in [17] that STAR is more efficient in terms of communication overhead even than the best performing on-demand routing protocol, DSR [22].

*Fisheye State Routing (FSR)*: In FSR [34], each node stores its neighbor list, the total topology of the network, and distance and next hop to each possible destination. Nodes are divided into "scopes" according to their hop distances and the topology updates are done more frequently in nearer scopes. Therefore, as a packet gets nearer to a destination, its route becomes more accurate. The most important feature of FSR is its scalability. Since the update messages that are sent by a node are almost limited to its neighbors, FSR can easily adapt to huge topologies.

*Location Aware Routing with Reduced Location Maintenance (LARRLM)*: In this protocol [26,27], each node knows the positions of all other nodes as well as its own. The nodes calculate their positions and if the position change of a node is more than a threshold since the last broadcast, it sends out a beacon message. In order to reduce the messaging for location information, route manager nodes are used. Each node must be neighbor to a route manager.

### Reactive Routing Protocols

*Ad Hoc On-Demand Distance Vector Routing (AODV)*: When a node does not know the route to its destination, it initiates a "path discovery process". It transmits a "route request" (RREQ) to its neighbors, and the neighbors transmit to their neighbors. The process stops when either the destination or an in-between node with a fresh enough route to the destination is found. Afterwards, the source is informed via a "route reply" (RREP) packet. The freshness of the routes is determined using destination sequence numbers. Each node only maintains data for its "active" routes, i.e. the routes that have recently been used in a certain period of time. When a route expiration timeout occurs, the current route is discarded and a new one should be discovered. [30,36]

*Dynamic Source Routing (DSR)*: DSR [22] consists of route discovery and route maintenance phases. In the discovery phase, RREQ packets are used with the same procedure in AODV. When the route is found, the RREP packet is sent on the same route if it is a symmetric link. Otherwise, it is piggybacked on a new RREQ packet. In the maintenance phase, route error packets are used. When the data link layer of a node reports a fatal transmission error, that node transmits an error packet. As a result, the source truncates the routes which include that node.

*Temporally Ordered Routing Algorithm (TORA)*: This algorithm [33] aims to decrease the communication overhead by discovering multiple routes on route setup. In case of a link failure, if there are still operational routes, no action is taken. When the network is partitioned due to a link or node failure, it is detected and propagated in the network. Routing loops are avoided by defining "heights" to nodes. The direction of a link is from the node with larger height towards to the one with smaller height. Besides its advantage of decreased number of control packets, TORA needs to be synchronized to a certain precision.

*Signal Stability Routing (SSR)*: SSR [15] uses the signal strength as routing metric. It is composed of two cooperatively running protocols, dynamic routing protocol (DRP) and static routing protocol (SRP). DRP maintains signal stability table and routing table, and also receives the transmissions. SRP checks the received packets and if the packet is for that node, SRP stacks the packet. Otherwise, it looks up the routing table to find the next hop. If no entry is found, search process is initiated by sending a route request packet (RREQ). RREQ packets are propagated through the links that are strong in terms of signal strength and that has not processed the request. Destination acknowledges the RREQ. Therefore, either the shortest path or the least congested path is found. DRP sends RREP packets and updates the routing tables. Route-search packets received from weak channels are dropped. But if no path has been found, weak channels are accepted. On the case of a link failure, the source is interrupted and a new search begins.

*Relative Distance Microdiversity Routing (RDMAR)*: This protocol [4] estimates the distance of the route in terms of hops and limits flooding. RDMAR counts on fixed node velocity assumption and uses the previously recorded distances to estimate the final distance. If a node discovers a link failure, it initiates a local route discovery process in order to discover a new partial path. If the failure is closer to the source, the source is informed.

*Location Aided Routing (LAR)*: LAR [24] limits the search in a smaller request zone. Nodes that receive the request, but that are out of the request zone ignore the request. However, this protocol requires knowledge of the positions of the nodes (GPS may be a solution).

*Power Aware Routing (PAR)*: In PAR [41], the routing criterion is the energy level of the nodes. The route discovery process tries to find the path consisting of the nodes that have higher energy levels. In that way, the energy of the nodes is uniformly used. PAR tries to minimize the variance in the energy levels and the energy consumed per packet; whLE trying to maximize the time before the network partitions due to the death of a node which has depleted its power source. This type of routing will be further studied in Section 2.2.

*Associativity-Based Routing (ABR)*: In order to minimize the control overhead due to the mobility of the nodes, ABR [44, 45] tries to use the most stable links. Every node sends periodic beacons and the node with the most number of beacons is the most stable node. In the route discovery phase, the path with the greatest associativity (i.e. the number of beacons) with the least number of hops is chosen. In case of a link failure, depending on the distance of the broken link to the destination, either a local search is utilized, or the path is discovered from the beginning.

### Hybrid Routing Protocols

*Zone Routing Protocol (ZRP)*: A routing zone is a collection of nodes whose hop distance to the center node is no longer than a zone radius [26]. In ZRP [18], each node acts as a zone center as well as a member of another zone. Within zones, routing is based on routing tables. If the destination is out of the zone, a route discovery process is initiated.

*Zone-Based Hierarchical Link State Routing (ZHLS)*: In ZHLS [21], every node and zone are given ID numbers. When a node has data to transmit to a node which is out of its zone, it sends queries to all other zones. When a gateway node finds out that the destination node is in its zone, it replies to the query.

**Overview of Routing Strategies**

According to the structure, properties and the purpose of an ad hoc network, the routing protocol to be used must be chosen carefully. The main differences between the three main routing approaches can be summarized as follows.

Proactive protocols should be used in slowly changing topologies since in rapidly changing topologies, control overhead will blow up. Also, proactive protocols will consume unnecessary storage area if topology changes are frequent. Therefore, in networks with high node mobilities, on-demand protocols should be preferred. Another important issue is scalability. Since ad hoc networks are open to any computing device nearby, number of nodes in a network is unlimited. So, in the case of a large scaled network, hierarchical routing is preferable. Sensor networks is a typical example. A network of sensors may consist of tens of thousands of nodes and typically, these nodes collect information about their geographical neighborhood and their mobility is low. Therefore, a clustering scheme would suit to a sensor network where nodes that acquire similar information are clustered and cluster heads connect to a central node.

Concerning scalability, clustering is a very effective way of handling large and dynamic networks. The whole network is partitioned into possibly overlapping clusters with the cost of extra messaging and with the risk of a reclustering in some part of the network causing the whole network to recluster. However, several successful clustering algorithms have been proposed. Some of the approaches to clustering problem are dominating set-based, low-maintenance based, mobility-aware, energy-efficient, load-balancing and combined-metric clustering algorithms [51].

### 2.1.3 Quality of Service (QoS) in Ad Hoc Networks

QoS is a set of measurable, predefined service requirements that need to be met by the network. Some examples are bandwidth, jitter, bit error rate, power management, security etc. QoS consists of two types of attributes. *Concave attributes* are the minimum of the constituent values, such as bandwidth and security. *Additive attributes* are the sum of the constituent values, such as jitter and end-to-end delay.

Due to the characteristics of the ad hoc networks such as mobility, limited power source and unexpected topology change, QoS is a significant issue. Some of the important QoS variables in ad hoc networks are summarized below layer by layer.

In the physical layer, adaptive modulation techniques, transmission power management and channel estimation are important problems. Concerning MAC layer, there is the issue of prioritizing the services as best-effort and real-time traffic. On the other hand, starvation of the low priority traffic should be eliminated. Black Burst Contention Scheme can overcome this problem [31]. In the network layer, constraint-based and multi-path QoS routing methods are the foremost methods. Constrained-based routing tries to satisfy some predefined values such as bandwidth. A path with more hops may be preferred to another one which can not satisfy the QoS metric. In multi-path QoS routing, more than one route are set up in order to support QoS metrics. When the QoS requirements are heavy, connection-oriented rather than connectionless services are preferred.

By nature, nodes in ad hoc networks should act cooperatively. However, in order to satisfy QoS requirements, some nodes may act selfish or greedy. A node may choose not to relay the packets it receives in order to save power, or may select smaller back off values in the MAC protocol. To prevent this behavior, protocols can be modified to punish the nodes that spoil the cooperative behavior or to reward the nodes that act in accordance to the protocol [13].

Power-awareness is another important issue since ad hoc nodes generally run on limited power sources. In some extreme cases even, such as sensor networks, the nodes die out when they completely deplete their batteries. Therefore, the protocols at each layer should take power management into account. Physical layer protocols should have adaptive transmission power features. MAC and network layer protocols should try to minimize the control overhead. As a special intermediate level feature, clustering process should also be power-aware if used.

## 2.2 Power Aware Routing

Most of the routing protocols for ad hoc networks were adopted from existing wired–network routing which need not consider power consumption since its nodes are usually powered by an energy network, or from cellular wireless networks whose base stations (i.e. routers) are also powered not by batteries, but infinite power sources. Therefore, these protocols do not account for power consumption of the routing process. However, ad hoc nodes generally run on limited battery power. In some extreme cases as sensor networks, a node is completely lost and wasted as soon as it depletes its energy supply. So, power–awareness is an important aspect of ad hoc routing.

One of the earliest efforts for this purpose is the Power–Aware Routing (PAR) Protocol proposed in [41]. PAR tries to relay the packets through the nodes with more left energy. Five metrics are desribed for power–aware routing:

- Minimize the energy consumed per packet,
- Maximize the time before the network partitions due to a node depleting its supply,
- Minimize the variance in node power levels,
- Minimize the cost per packet, and
- Minimize maximum node cost.

The results of simulations for PAR are reported in [41]. In these simulations, PAR is run on top of Power–Aware Multi Access Protocol with Signalling (PAMAS) [40] which is a power–aware MAC protocol. It is claimed in [41] that PAR delivers an improvement of 5-30% in terms of cost/packet on top of a further improvement of 40-70% thanks to PAMAS.

Recently, research on power–aware routing for ad hoc networking has got popular and many protocols have been proposed. In [25], a review of these protocols are given. Figure 2.1 summarizes the taxonomy of power–aware routing protocols. Power–aware routing is classified into two main categories as activity–based and connectivity–based methods. Activity–based methods are related to direct actions such as transmitting a packet. Connectivity–based methods address the problem in a more generalized manner. Activity–based methods are further divided into two categories as multicasting/broadcasting and unicasting methods, whose difference is self-explainatory.

Unicasting activity–based protocols are of two groups. Active energy–saving methods try to minimize the total consumed power per packet by choosing minimum energy paths. Maximizing network lifetime methods on the other hand, aim to evenly distribute the energy consumption among all nodes.

Connectivity–based protocols is also divided into two groups. Topology control mechanisms adjust mobile nodes' transmission power. When a node increases its transmission power, new nodes become neighbors. In this manner, the protocol adjusts the topology of the network. Passive energy–saving methods turn off idle nodes and save power. This method is also used in some MAC protocols such as PAMAS.

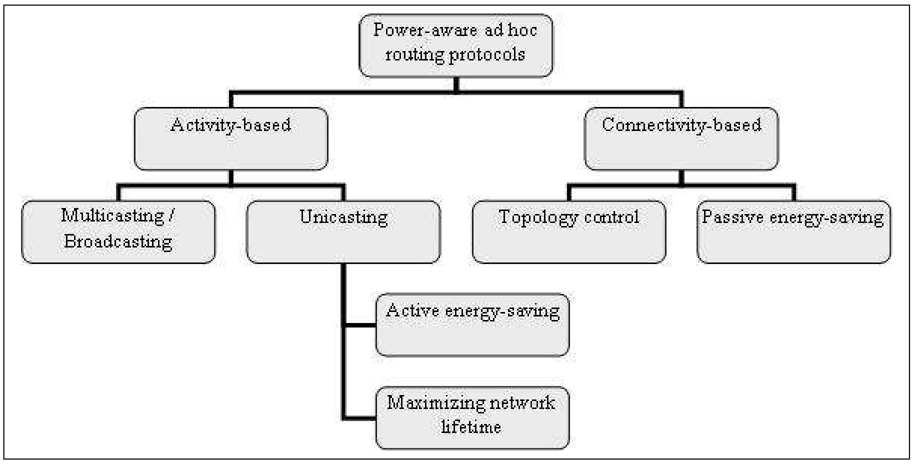

Figure 2.1: Categorization of power–aware routing protocols [25]

According to the path loss model for wireless communications, if the distance between two communicating wireless nodes is $d$, the signal strength of the transmission drops by a factor of $d^n$ where $n \geq 2$ [37]. For example, for Free Space Propagation Model [37], $n$ is 2 and for Two-Ray Ground Reflection Model [37], $n$ is 4. Consider Figure 2.2. The total power needed to transmit from node A directly to node C is $t \cdot {d_{AC}}^n$ where $d_{AC}$ denotes the distance between nodes A and C, and $t$ denotes the power threshold for node C to succesfully hear the transmitted signal. On the other hand, if node B relays the packet from node A to node C, the total power needed is $t \cdot ({d_{AB}}^n + {d_{BC}}^n)$ which clearly is less than $t \cdot {d_{AC}}^n$ when $n \geq 2$ [38]. Also, a certain amount of power is consumed by the intermediate node due to signal reception, but this amount is less than the cost of excess power due to stronger and direct transmission unless the nodes are too close.

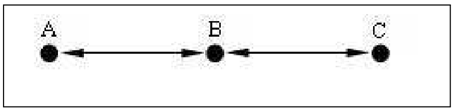

Figure 2.2: Intermediate routing with three colinear nodes

Using this property of wireless propagation, intermediate routing can save considerable amounts of power [25]. In [38], the concept of *relay region* is presented. Each wireless node has its own relay region. If a node wants to transmit to a neighbour which is inside its relay region, using an intermediate relay node is better in terms of total power consumption.

## 2.3 Game Theory

Game Theory [14] is a collection of mathematical tools that model the interaction of participants in a strategic situation. The goals of the agents involved in the situation may be either conflicting, or cooperative. Game Theory is mainly used in economic theory but it is also applied to many areas of science ranging from biology to communication theory.

### 2.3.1 Game Theory in Communications

In communication systems, selfish nodes that act according to their own welfare rather than overall system performance is quite common [29]. Therefore, game theory is a perfect tool not only to analyze the effects of such nodes on the performance of the communication protocol utilized, but also to design selfishness-aware protocols. Moreover, it can be utilized for designing protocols that consider the operations in a cooperative manner and decide regarding the overall welfare. Furthermore, being a distributed optimization scheme, it provides scalability which is strongly desirable in communication protocols [29].

Regarding wireless networks, game theory has been used to model 802.11 Distributed Coordinated Function (DCF) [47], to model random access schemes in ad hoc networks [28], to devise power control strategies [28, 29] and to design routing protocols [10, 11].

In [28], a new game theoretic version of well-known Aloha protocol [3] is described. The new protocol is based on a "collision game." Ref. [47] models the DCF [1, 2, 6] by defining a DCF game with two nodes as players. Fairness of DCF, on the other hand, is investigated in [47] and it is stated that DCF is extremely unfair when it supports TCP traffic. As a solution, a fairness game is proposed in [47] as an alternative to Binary Exponential Backoff (BEB).

### 2.3.2 Power Control Through Game Theory

MacKenzie and Wicker discuss power control games for wireless networks in [28] and [29]. In power control games, a node's utility increases with its signal-to-interference-and-noise ratio (SINR) and decreases with its transmission power level. While a utility function adopted from [39] is given in [28], it is also stated that the issue of a proper utility function needs further research. Moreover, the networks analyzed in [28] are cell-based networks. Power utility functions for ad hoc networks may differ from those of cellular networks.

Ref. [29] explains two versions of a power control game. One type of the power control games is the refereed game, where the base station acts as a referee. The other type is called the repeated power control game, where the base station ceases to be the referee. Repeated power control game is more suited for ad hoc networks since there is no central referee. However, the base station still has a function in this method. Therefore, in order to use this method in ad hoc networks, this function must be eliminated or distributed.

### 2.3.3 Routing in Ad Hoc Networks using Game Theory

A novel routing protocol based on Shapley value [14] is presented in [10]. The main idea of Contribution rewArd routing Protocol with Shapley Value (CAP-

SV) is to prevent the nodes from acting selfishly in terms of power consumption and hence improving the overall network life-time. Instead of trying to eliminate the selfish nodes, CAP-SV uses a virtual currency system to reward the cooperative nodes. The Shapley value, described by Lloyd Shapley in 1953, is a measure of an agent's contribution to the game. This concept is used in CAP-SV for determining each node's payoff.

Another routing protocol for ad hoc networks based on game theory is described in [11]. This protocol, named Transmission power rEcursive Auction Mechanism (TEAM) is very similar to CAP-SV. The underlying idea which is stimulation of cooperation is also present in TEAM. The only significant difference is that TEAM performs redirection of routes through an iterative auction mechanism.

CAP-SV is explained in more detail in the next chapter.

# Chapter 3

# CAP-SV Performance

Performance analysis of a recently proposed power–aware routing protocol, Contribution Reward Routing Protocol with Shapley Value (CAP–SV) [10] is done and the results obtained are compared to those obtained via simulations only by Cai and Pooch [10]. Also, performance analysis is presented for some scenarios not covered in [10].

## 3.1 Contribution Reward Routing

CAP–SV consists of two main phases. The first phase, route discovery phase is the same as AODV. A node that does not have a route to the destination sends out a RREQ packet. When the RREQ arrives at the sender or another node that has a route to it, a RREP packet is sent.

After the route discovery phase comes the coalition setup phase. In CAP–SV, the amount of power which a packet is transmitted with is writeen into that packet's header by the transmitter node. Therefore, the receiver can calculate the minimum power that the sender should transmit in order to reach it. In this analysis, we adopt the *Two-Ray Ground Reflection Model* [37] as assumed in [10]. According to this model, the relationship between the power a signal is transmitted by the source and the power it is received at the receiver is given by the formula

$$P_r = \frac{P_t \cdot G_t \cdot G_r \cdot (H_t^2 \cdot H_r^2)}{d^4} \tag{3.1}$$

where $G_t, G_r, H_t$ and $H_r$ are constants that reflect the properties of the transmitter and receiver antennas, and $d$ is the distance between the source and the receiver nodes. So, the power of the received signal can be represented as

$$P_r = \frac{K \cdot P_t}{d^4} \tag{3.2}$$

where $P_t$ denotes the power level the signal is transmitted. Since $P_{min}$ is the value yielding a received power level of $P_{thr}$, the threshold for capturing a signal from the air, at the receiver,

$$P_{thr} = \frac{K \cdot P_{min}}{d^4} \tag{3.3}$$

Combining (3.2) and (3.3), the minimum power is found as

$$P_{min} = \frac{P_t \cdot P_{thr}}{P_r} \tag{3.4}$$

The receiver informs the sender of this value. Using these power values, when a node hears a RREP, it checks whether the total power consumption will reduce if the route is redirected on it. If that is the case, it sends out a redirection (RRDR) message. However, there may be more than one redirectors for a route. To prevent the collision of RRDR messages, a redirector node waits for a period of time inversely proportional to its improvement ratio ($R_{imp}$). $R_{imp}$ of a node $i$ is the ratio of the reduction in power consumption when the route is redirected on $i$ to the power consumption when the route is not redirected at all; i.e.

$$R_{imp} = \frac{P_{sr} - (P_{si} + P_{ir})}{P_{sr}} = 1 - \frac{P_{si} + P_{ir}}{P_{sr}} \tag{3.5}$$

where $P_{mn}$ denotes the power consumed for node $m$ to transmit to node $n$; $s$, $i$ and $r$ being the source, redirector and the receiver respectively. This redirection mechanism is iterative. After the final route setup, all participating nodes are awarded with virtual currency proportional to their contributions. This value is calculated using the Shapley value. For the payments, a virtual currency system such as Nuglets [9] may be used.

*Shapley value* was proposed in 1953 by Lloyd Shapley. Shapley value assigns a unique value to each outcome of an $n$-player cooperative game. Then, Shapley values for every player can be calculated by measuring how much their cooperation improves the result. In our case, the outcome corresponds to the total power consumption of a route. As nodes are added during the redirection phase of CAP–SV, the total power consumption reduces, hence the outcome improves. After the route is set, every player's contribution can be calculated by measuring how much power its participation has saved.

All payments in CAP–SV are made after the data transmission occurs successfully. The nodes participating in the route before redirections also receive payoffs. Therefore, a node receiving a data packet definitely chooses not to drop the packet in order to get the payoff. A redirector candidate, on the other hand, in order to receive payoff, may greedily decide that it would be able to relay the data packet using less power. If this is already the case, there would be no problem either for this node, or the original node since both receives payment if the transmission is successful. However, if the node is incapable of transmitting the packet with less power and yet greedily announces this value, the transmission will fail and it receives no payment although it wastes some power. Therefore, cheating is irrational and so, playing truthfully is the rational choice for all nodes in CAP–SV [10, 11].

After a period of time, some nodes which are positioned in some strategic points become one of the wealthiest in their neighborhood. Therefore, in order not to deplete their power levels, they go to sleep for a certain period of time if they are among the top richest in their neighborhood, the top richest being defined by a threshold, $\gamma$, referred to as the *richness ratio.* Each node is aware of the wealths of its neighbors since a node writes its wealth information into the periodic *Hello* packets. Simulation results presented in [10] show that CAP–SV improves network life-time over AODV while its packet delivery rate is slightly lower.

## 3.2 Protocol Performance

First, the redirection overhead of CAP-SV is analyzed. This is done by assuming a redirection packet size, and calculating the average number of redirection packets generated. Then, left energy per node is approximated using the power consumption relations given in [16]. Lastly, the results are compared to those of [10].

### 3.2.1 Redirection Overhead

As explained in section 3.1, two-ray ground reflection model is assumed. In this model, the required transmission power is proportional to the $4^{th}$ power of the distance between the transmitter and the receiver. In order to redirect an existing one-hop path between the nodes $s$ and $r$ over the node $i$, the formula

$$P_{si} + P_{ir} \leq \alpha \cdot P_{sr} \tag{3.6}$$

where $P_{mn}$ denotes the minimum power needed to transmit from node $m$ to node $n$, should hold. $\alpha$ is a protocol parameter that directly affects the number of redirector candidates. The smaller $\alpha$, the less number of redirector candidates there are. Taking $P_r$ equal to $P_{thr}$ and rearranging (3.2), we obtain the formula for $P_{mn}$ as

$$P_{mn} = \frac{P_{thr} \cdot d_{mn}^4}{K} \tag{3.7}$$

So, (3.6) becomes

$$\frac{P_{thr} \cdot d_{si}^4}{K} + \frac{P_{thr} \cdot d_{ir}^4}{K} \leq \alpha \cdot \frac{P_{thr} \cdot d_{sr}^4}{K} \tag{3.8}$$

which reduces to

$$d_{si}^4 + d_{ir}^4 \leq \alpha \cdot d_{sr}^4 \tag{3.9}$$

In order to calculate the average number of redirection packets for a given $\alpha$, we need to define a *redirection region.* Assuming that the distance between the nodes $s$ and $r$ is $d$ meters, we may set up the coordinate system given in Fig. 3.1. Now, we can determine the Euclidean distances between the nodes according to this coordinate system.

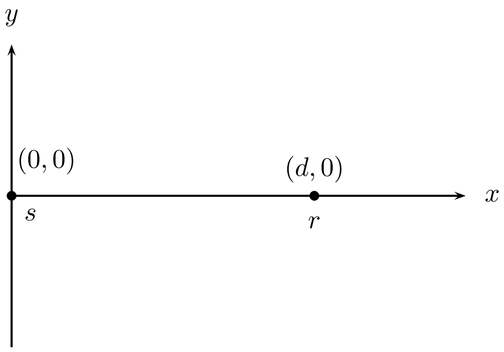

Figure 3.1: Coordinate system for defining the positions of the nodes $s$ and $r$

$$\begin{aligned} d_{si}^4 &= \Big((x_s - x_i)^2 + (y_s - y_i)^2\Big)^2 \\ d_{ir}^4 &= \Big((x_i - x_r)^2 + (y_i - y_r)^2\Big)^2 \\ d_{sr}^4 &= \Big((x_s - x_r)^2 + (y_s - y_r)^2\Big)^2 \end{aligned} \tag{3.10}$$

Also substituting the values $x_s = 0$, $y_s = 0$, $x_r = d$ and $y_r = 0$, (3.9) becomes

$$\left(x_i^2 + y_i^2\right)^2 + \left((x_i - d)^2 + y_i^2\right)^2 \leq \alpha \cdot d^4 \tag{3.11}$$

which is the defining equation for the redirection region. This mathematical relationship produces an elliptic-like region that is shown in Fig. 3.2.

The points this graph crosses the $x$-axis are given by the expression

$$x = \frac{d}{2}\Big(1 \pm \sqrt{-3 + 2\sqrt{2(1+\alpha)}}\Big)$$

and the peak points are given by

$$y = \pm\frac{d}{2}\sqrt{-1 + 2\sqrt{2\alpha}}$$

which occur when $x = \frac{d}{2}$.

So, the area of the redirection region can be calculated as

$$R.A. = 2\int_{L(d,\alpha)}^{U(d,\alpha)} \frac{\sqrt{-d^2 + 2dx - 2x^2 + d\sqrt{-d^2 + 4dx - 4x^2 + 2\alpha d^2}}}{\sqrt{2}} dx \tag{3.12}$$

where

$$U(d,\alpha) = \frac{d}{2}\Big(1 + \sqrt{-3 + 2\sqrt{2(1+\alpha)}}\Big)$$

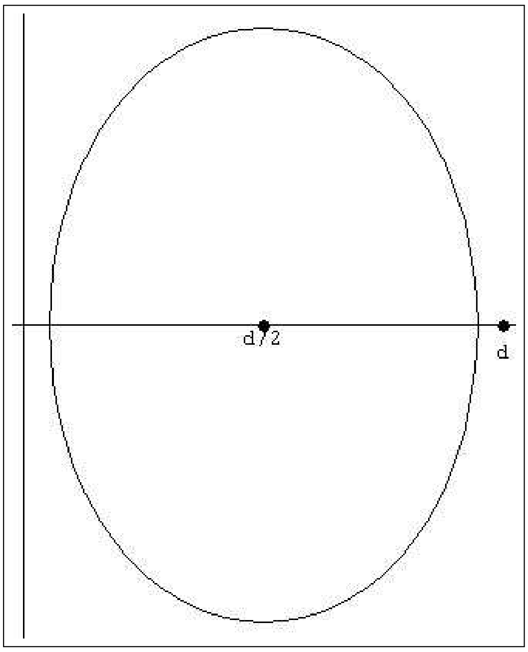

Figure 3.2: Graph of the redirection area produced by Mathematica®3.0

and

$$L(d,\alpha) = \frac{d}{2}\Big(1 - \sqrt{-3 + 2\sqrt{2(1+\alpha)}}\Big)$$

Within this region, the node with the best $R_{imp}$, as defined in (3.5), will redirect the route. That node is the one which is nearest to the midpoint $(\frac{d}{2}, 0)$.

A simulation program is written in C++ to observe the redirection process. The algorithm is roughly as follows:

1. Start with the points (0,0) and ($d$,0).
2. Calculate the redirection area. Multiply it by the node density to find the number of redirector candidates. If there are $< 1$ redirector candidates, exit.
3. Else, uniformly generate the redirector candidate points in the rectangular region defined by the peak points and the crosspoints.
4. Find the one which is nearest to the midpoint. Add it to the route.

5. Recursively run the same procedure on the `(source, redirector)` and `(redirector, receiver)` pairs.

Let $N_R$ denote the average number of redirections found by this algorithm.

In order to calculate the redirection overhead caused by the redirection messages, we need to assume a redirection message length since it is not specified in [10]. Let $M$ denote this length.

At every $T_H$ seconds, which is the Hello interval, all nodes running CAP-SV check their neighbor-lists. If a node finds out that it is among the most richest $(100 \cdot \gamma)\%$ of the neighbors, it goes to sleep. This is called *role rotation.* $\gamma$ has an important effect on the overall network lifetime. In [10], it is stated that the lifetime is proportional to $\frac{1}{1-\gamma}$. So, $\gamma$ is generally chosen large, such as 75%. As a limiting case, in order to ease the analysis, we may assume that role rotation happens at every $T_H$ seconds, and hence, the route breaks every $T_H$ seconds. The number of bytes transmitted for redirection in a period of $T_H$ seconds is then equal to

$$\text{(Num. of hops in the route)} \times \text{(RRDR Message Length)} \times \text{(Number of Redirections)}$$

$$= H \cdot M \cdot N_R$$

The total number of bytes transmitted in $T_H$ seconds including the redirection messages and the data communications is equal to

$$H \cdot M \cdot N_R + \text{(Arrival rate)} \times \text{(packet length)} \times \text{(Hello interval in sec.s)}$$

$$= H \cdot M \cdot N_R + \lambda \cdot F \cdot T_H$$

We are interested in finding the percentage of bytes transmitted for redirection in the total number of bytes transmitted. The number of total redirection bytes divided by the sum of redirection bytes and the traffic generated gives us the redirection overhead. So, the redirection overhead, $RO$, is equal to

$$RO = \frac{H \cdot M \cdot N_R}{H \cdot M \cdot N_R + \lambda \cdot F \cdot T_H} \qquad (3.13)$$

Inspecting (3.13), we can conclude that the overhead grows with the number of redirections and diminishes with larger packet sizes and arrival rates. This result applies to any traffic type including Poisson traffic since we only deal with the average (expected) number of packets in a second, which is equal to the arrival rate of a Poisson traffic.

### 3.2.2 Energy Consumption

We are going to assume a linear power consumption model. The amounts of energy spent for transmission and reception are linear in packet size, and the idle power consumption is constant. This assumption can be formulated as

$$P_t = P_{t\ell} \cdot F + P_{tc}$$

$$P_r = P_{r\ell} \cdot F + P_{rc}$$

where $P_t$, $P_r$ and $F$ denote the transmit and receive powers and the packet size respectively. Let $P_i$ represent the idle power. So, the total power consumed per second for AODV is

$$P_{per\,sec} = \lambda \cdot \Big( (P_{t\ell} + P_{r\ell}) \cdot F + P_{tc} + P_{rc} \Big) + P_i \cdot (1 - 2t_{tr}) \tag{3.14}$$

since a node transmits $\lambda$ packets a second. The time to perform packet transmission per second is

$$t_{tr} = \frac{\lambda \cdot F\,bytes \cdot 8\ bits/byte}{b} \tag{3.15}$$

where $\lambda$, $F$ and $b$ are arrival rate, packet size in bytes and bandwidth respectively.

When a node is transmitting, another node is receiving, and when the message is received, the receiver will transmit it to the next hop. So, on the average, a node spends transmit and receive powers given above during twice a packet transmission time, and spends idle power rest of the time.

On the other hand, when CAP-SV is run, the power consumption per transmission reduces dramatically. The simulator program mentioned in section 3.2.1 also calculates the power improvement using the hop-by-hop distances. Calling this power improvement ratio $P_{imp,\alpha}$, we may rewrite the energy consumption. The only difference will be that the transmission power consumption will be multiplied by $P_{imp,\alpha}$. This time, we need to distinguish the transmission and the reception power consumptions. Then, the transmission power per second becomes

$$P_{per\,sec} = P_{tx} \cdot P_{imp,\alpha} + P_{rx} + P_i \cdot (1 - 2t_{tr}) \tag{3.16}$$

where

$$P_{tx} = \lambda \cdot (P_{t\ell} \cdot F + P_{tc})$$

and

$$P_{rx} = \lambda \cdot (P_{r\ell} \cdot F + P_{rc})$$

The *sleep mode* is not included in (3.16). According to the *role rotation* procedure of CAP-SV, at every *Hello* interval, if a node finds out that it is among the top $(100 \cdot \gamma)\%$ richest of its neighbors, it goes to sleep mode. Therefore, we may assume that, at any given time, $(100 \cdot \gamma)\%$ of the node are sleeping, hence the probability of a node being in the sleep mode is $\gamma$. So the correct expression should be

$$P_{per\,sec} = \big(1 - \gamma\big)\big(P_{tx} \cdot P_{imp,\alpha} + P_{rx} + P_i \cdot (1 - 2t_{tr})\big) + \gamma\big(P_s\big) \tag{3.17}$$

where $P_s$ represents sleep power.

Using (3.17), we may define the left energy function of an average node as

$$E(t) = E_0 - P_{per\,sec} \cdot t \tag{3.18}$$

where $E_0$ is the initial energy of the node. Failure time, $T_{failure}$, is the solution to the equation $E(t) = 0$.

## 3.3 Numerical Evaluation

In this section, the results obtained in Section 3.2 are applied to the parameters of the simulation reported in [10], and the numerical results are compared to the simulation results reported in [10].

### 3.3.1 Redirection Overhead

Table 3.1 gives the parameters used in the simulations in [10]. Since CAP-SV uses AODV for discovering routes and AODV uses minimum hop metric, we

| | |
|---|---|
| Traffic type | CBR |
| MAC Protocol | IEEE 802.11 |
| Traffic rate | 3 × 128 byte packets/second |
| Comm. range of nodes | 250 $m.$ |
| Bandwidth | 2 Mbps |
| Simulation area | 500 $m.$ × 500 $m.$ |
| Number of nodes | 36, 56, 76 |
| Node distribution | Uniform over rectangular region |
| Initial energy/node | 100 J |
| Transmission power | 1.4 W |
| Receive power | 1.0 W |
| Idle power | 0.83 W |
| Sleep power | 0.13 W |
| $\alpha$ | Not Specified |

Table 3.1: Simulation environment of [10]

may assume that the maximum distance between two router nodes before the redirection occurs is 250 meters, which is the radio range of a node. Since the simulation area is a 500 $m.$ × 500 $m.$ field, the maximum possible distance between a source-destination pair is equal to $500\sqrt{2} \approx 707.11$ meters. This requires a 3-hop path as a worst case scenario. So, $H$ will be taken as 3.

The simulation program to find the average number of redirections described in Section 3.2.1 was run 100 times with the $\alpha$ values of 0.25, 0.5, 0.75 and 1. The average number of redirections in each case are listed in Table 3.2. The observation here is that the number of redirections does not change very much with node density. On the other hand, $\alpha$ affects this value dramatically.

| $\alpha$ | 0.25 | 0.50 | 0.75 | 1.00 |
|---|---|---|---|---|
| 36 nodes | 1.00 | 2.68 | 4.15 | 5.26 |
| 56 nodes | 1.02 | 2.64 | 4.10 | 5.25 |
| 76 nodes | 1.00 | 2.71 | 3.98 | 5.48 |

Table 3.2: Average number of redirections

CAP-SV header length is also not specified, so its length will be assumed to be equal to the header length of a typical network layer protocol, IP, which is typically 20 bytes [43]. The MAC protocol used is IEEE 802.11, so the MAC header length is known [1, 2]. The remaining part is the data itself. A redirection message is expected to announce its address, its $R_{imp}$ and the route it is redirecting. The details of the assumed packet is given in Table 3.3. With these assumptions, the RRDR message length $M$ is found to be 70 bytes.

| *CAP-SV header* | 20 B |
|---:|---|
| *IEEE802.11 header* | |
| Frame Control | 2 B |
| Duration/ID | 2B |
| Address | 24B |
| Sequence Control | 2B |
| CRC | 4B |
| *Redirection Information* | |
| Node's Own Address | 4B |
| $R_{imp}$ | 4B |
| Route Source Address | 4B |
| Route Receiver Address | 4B |
| *TOTAL* | 70B |

Table 3.3: Redirection Packet Length Assumptions

Substituting $H = 3$, $M = 70$, $\lambda = 3$, $F = 128$ and $T_H = 10$ into (3.13), the overhead in terms of number of redirections becomes

$$RO = \frac{3 \cdot 70 \cdot N_R}{3 \cdot 70 \cdot N_R + 3 \cdot 128 \cdot 10}$$

The graph of this function is given in Fig. 3.3. This figure is compared with the results obtained in [10] via simulation in chapter 4 below.

Fig. 3.4 shows the delivery rate trend obtained via the simulations in [10]. It is seen that the delivery rate obtained with CAP-SV is 5-10% less than the delivery rate obtained with AODV. This is due to the redirection overhead. Checking Table 3.2, it is seen that maximum number of redirections is around

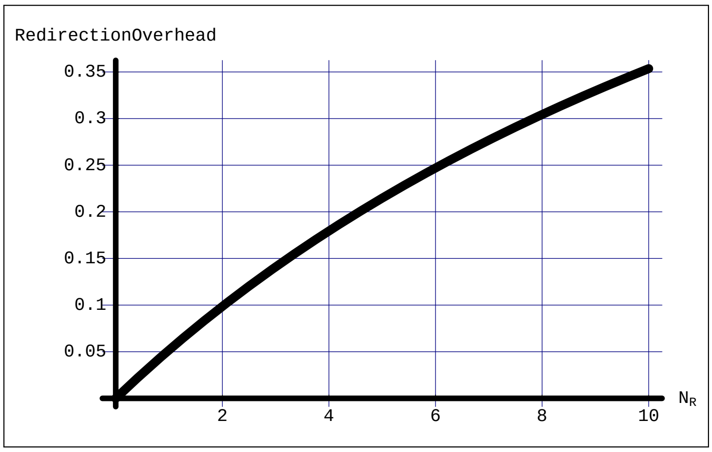

Figure 3.3: Overhead function graph

5. This corresponds to an overhead of 20% according to Fig. 3.3. The difference between the overhead amounts is because of our assumption that redirection occurs every Hello interval. In reality, this may happen less frequently.

### 3.3.2 Energy Consumption

Feeney and Nilsson report the energy consumption of a wireless interface in [16]. They model the energy consumption as a linear function of the packet size, $F$. Table 3.4 shows these functions for a 2Mbps wireless interface card.

| | $\mu W \cdot sec/byte$ | $\mu W \cdot sec$ |
|---|---|---|
| point-to-point send | 1.9 $\times size$ | +454 |
| point-to-point recv | 0.50 $\times size$ | +356 |
| idle (ad hoc) | 843 $mW$ | |

Table 3.4: Part of Linear model power consumption measurements from [16]

Therefore, the parameters of our linear model described in Section 3.2.2 becomes

$$\begin{aligned} P_{t\ell} &= 1.9\,\mu W \\ P_{tc} &= 454\,\mu W \end{aligned}$$

$$\begin{aligned} P_{r\ell} &= 0.50\,\mu W \\ P_{rc} &= 356\,\mu W \\ P_i &= 843\,mW \end{aligned}$$

Concerning the simulation setup of [10], a node tranmits three 128-byte packets per second which means that $\lambda = 3$ and $F = 128$. This results in a transmission time of

$$t_{tr} = \frac{3 \cdot 128\,bytes \cdot 8\;bits/byte}{2 \times 10^6\,bps} = 1.536\,msec$$

The total power consumed a second with AODV is therefore

$$P_{per\,sec} = \lambda \cdot \Big( (P_{t\ell} + P_{r\ell}) \cdot F + P_{tc} + P_{rc} \Big) + P_i \cdot (1 - 2t_{tr}) = 843.762\,\mathrm{mJ}$$

Knowing that a node consumes 843.762 mJ a second, the expected lifetime of the network can be calculated. From Table 3.1, we know that a node starts with 100 J of energy. Therefore, the expected time that the network fails due to power outage is

$$T_{failure} = \frac{100\,\mathrm{J}}{843.762\,m\mathrm{J}/sec} = 118.517\,sec \tag{3.19}$$

Fig.s 3.4, 3.5 and 3.6 are the results obtained by simulation and are reported in [10]. The failure time found in (3.19) fits very well to the abrupt failure in Fig.s 3.4 and 3.5, and to the linear decrease in Fig. 3.6 and the failure at $t = 120$.

As expressed in Section 3.2.2, our simulator program calculates the power improvement. This value is calculated by taking the ratio of the total power consumption on the redirected path to the power consumption of the single hop. Therefore, a smaller value means a better improvement. Using the same set of runs given in Table 3.2, the power improvement values in Table 3.5 are obtained.

Similar to the overhead analysis of section 3.2.1, the conclusion of node density not seriously affecting the improvement can be drawn from the values in Table 3.5. On the other hand, it can be claimed that greater $\alpha$ values yield better power improvements.

| $\alpha$ | 0.25 | 0.50 | 0.75 | 1.00 |
|---|---|---|---|---|
| 36 nodes | 0.1020 | 0.0267 | 0.0162 | 0.0123 |
| 56 nodes | 0.0979 | 0.0292 | 0.0155 | 0.0116 |
| 76 nodes | 0.0999 | 0.0293 | 0.0160 | 0.0126 |

Table 3.5: Average power improvements

For the sake of illustration, we will calculate the $T_{failure}$ for the $\alpha$ value 0.50 and 56 nodes. Using (3.17), assuming a $\gamma$ value of 0.75 and since $P_{idle} = 0.13\,W$ from Table 3.1, the power consumption is found as $P_{per\,sec} = 307.933\,\text{mJ}$

So, the expected failure time becomes

$$T_{failure} = \frac{100\,\text{J}}{307.933\,m\text{J}/sec} = 324.75\,sec$$

Some failure times are given in Table 3.6 for some $\alpha$ and $\gamma$ values. These values show that the failure times are improved over pure AODV, as also illustrated by Cai and Pooch in [10]. It can be claimed that the failure time does not much depend on $\alpha$, it rather changes significantly with $\gamma$.

|  | $\gamma = 0.50$ |  |  | $\gamma = 0.75$ |  |  |
|---|---|---|---|---|---|---|
|  | 36 nodes | 56 nodes | 76 nodes | 36 nodes | 56 nodes | 76 nodes |
| $\alpha = 0.5$ | 205.82 | 205.82 | 205.82 | 324.75 | 324.75 | 324.75 |
| $\alpha = 1.0$ | 205.83 | 205.83 | 205.83 | 324.76 | 324.76 | 324.76 |

Table 3.6: Failure times for some $\alpha$ and $\gamma$ values

This conclusion, however, might change with scenarios having denser traffic, i.e. larger packet sizes and/or greater rates. Because, $\alpha$ significantly affects the number of redirectors, which in turn affects $P_{imp,\alpha}$. Considering (3.17), if the traffic gets denser, transmission time may become comparable to idle time and $P_{imp,\alpha}$ will have a greater affect on $P_{per\,sec}$.

Using (3.18) and the values in Table 3.6, analytical curves for the left energy of a node are shown in Fig. 3.6. These curves prove that our analysis results fit with the results obtained in [10] via simulations in the linear portions. Towards the end of the simulations, the number of living nodes reduce and therefore the value of left energy per *living* node reduces more slowly.

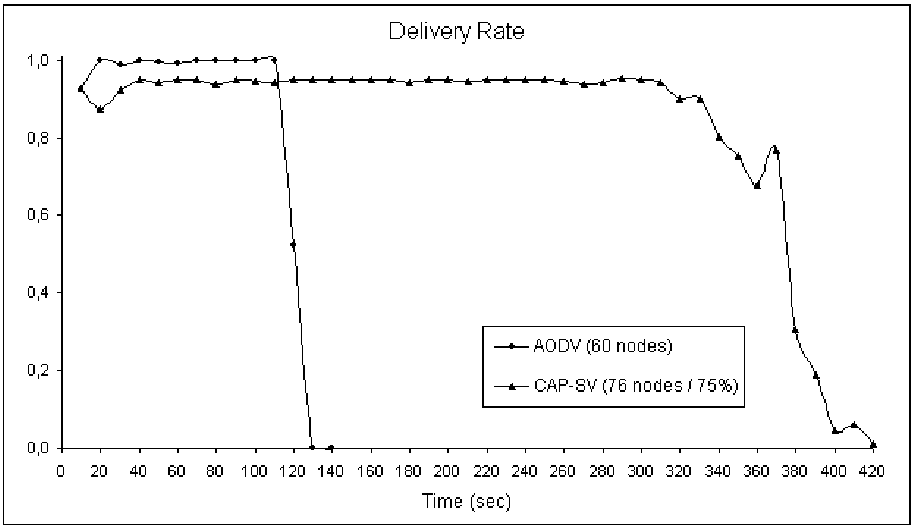

Figure 3.4: Delivery rate with different scenarios, curves taken from [10]. CAP-SV $\gamma$ value is 0.75

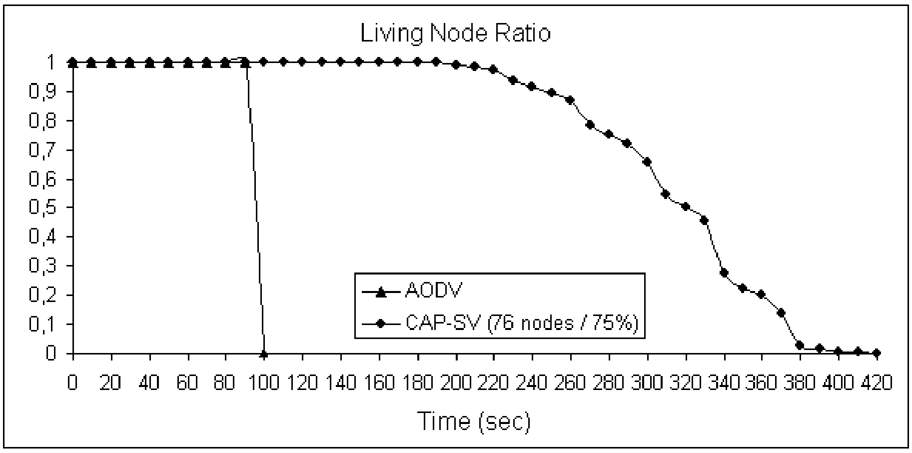

Figure 3.5: Living node ratio with different scenarios, curves taken from [10]. CAP-SV $\gamma$ value is 0.75

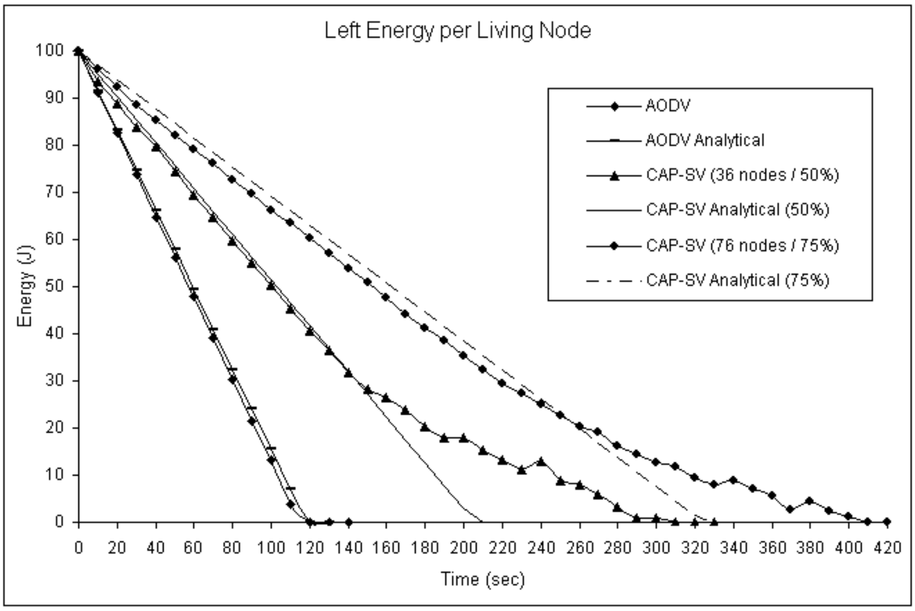

Figure 3.6: Left energy per living node with different scenarios, simulated curves taken from [10]. Percentages denote $\gamma$ value.

# Chapter 4

# Discussion and Conclusion

On a general scale, considering (3.13), the routing overhead increases with the number of redirections and reduces with larger packet sizes, and is influenced by traffic characteristics. This study has considered CBR traffic only, with the purpose of comparing analytical results with simulations reported in the literature [10]. Our results apply to Poisson traffic but behavior under different traffic characteristics needs to be further investigated.

Concerning the power consumption, the results shown in Fig.s 3.4, 3.5 and 3.6 are verified in section 3.2.2 using the linear power consumption model presented in [16], and the power gain of CAP-SV is illustrated.

There is a trade off between the routing overhead and the power consumption improvement. As $\alpha$ is increased, routing overhead increases, but also the power gain is improved. If $\alpha$ is taken smaller, routing overhead is minimized at the cost of gaining less power improvement. However, this does not hold at lower traffic rates since the idle time dominates. If this is the case, $\alpha$ value does not affect the protocol performance.

On the other hand, the richness ratio, $\gamma$, is another protocol parameter that directly affects the protocol performance no matter what the scenario is. Generally, higher $\gamma$ values yield better performance in terms of network lifetime.

## 4.1 Future Work

The power aware routing protocol, CAP-SV, defined in [10] is promising in terms of power consumption reduction and network lifetime maximization. However, the simulation study provided in [10] is far from sufficient. The $\alpha$ value used in the simulations is not provided. However, the impact of the value of $\alpha$ on the performance should be studied extensively via simulations.

Another unaddressed issue is mobility. The performance of a protocol that performs very well in a static topology may severely degrade under mobility. So, mobility studies should be made.

Lastly, the performance of CAP-SV should be compared to those of other power-aware routing protocols such as PAR [41] under a variety of scenarios including different traffic models, rates and mobility models.

In general, as this study has been purely analytical, it has provided insight in a general sense and has served to validate the simulation-based results reported in the literature. Further studies to address specific scenarios, however, will always be necessary.

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