Multipath Routing for Wireless Sensor Networks: a Hybrid between Source Routing and Diffusion Techniques

Mohamed Ebada

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Abstract:

In this thesis, an investigation of the performance of multipath routing in Wireless Sensor Networks (WSN) is performed. The communication in the network under study is to take place from individual nodes to the sink node. The investigation involved multipath finding methods in WSN. Also, it involves investigating the weight assignment, traffic splitting and route selection methods for the different paths discovered by each node in the WSN. Also, a comparison between Hybrid Routing Protocol, Source Routing Protocol and Diffusion Routing Protocol is performed. A simple traffic routing algorithm for each routing protocol has been developed to conceptualize how the network traffic is routed on a set of active paths. The investigation of the Hybrid, Source and Diffusion Routing Protocol involved using multiple paths simultaneously to transmit messages that belong to the same flow by using a weight assigned to each path and transmit each message as a whole. Finally, the power consumption and the QoS in terms of message delays for a WSN were investigated and compared between different protocols.

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List of Acronyms:

APRP	Alternate Path Routing Protocol
CMRP	Concurrent Multipath Routing Protocol
CP	Circular Path
DLP	Duplicated Path
DP	Disjoined Path
DRP	Diffusion Routing Protocol
EARP	Energy Aware Routing Protocol
GLS	Generalized Load Sharing
GLS	Generalized Load Sharing
HRP	Hybrid Routing Protocol
J2E	Java Enterprise Edition
JP	Joined Path
LP	Long Path
LSM	Load Sharing Method
MFP	Multipath Finding Protocol
MFPE	Multipath Finding Protocol Efficiency
MPR	Multipath Routing Protocol
NCF	Network Connectivity Factor
NHF	Network Hops Factor
NPP	Non-Primary Path

NRE	Network Routing Efficiency
NRE	Network Routing Efficiency
NRF	Network Routing Factor
NRW	Normalized Residual Workload
NSF	Network Size Factor
PDP	Primary Disjoined Path
PLP	Parallel Path
PP	Primary Path
QoS	Quality of Service
RE	Routing Efficiency
RNW	Route Normalized Weight
RW	Route Weight
RWAM	Route Weight Assignment Method
SRP	Source Routing Protocol
TSP	Traffic Splitting Protocol
WSN	Wireless Sensor Network
WSNF	Wireless Sensor Network Factors
WSNL	Wireless Sensor Network Layers

List of Symbols:

c_f	Network Connectivity Factor
c_i	Number of nodes connected to node i
E	Multipath Finding Protocol Efficiency for the network
e_i	Multipath Finding Protocol Efficiency for a node i
H	Max. No. Of hops for a path
h_j	Number of hops for route j
j	Take values 1, 2, 3 …… t_i
j_i	Take values 1, 2, 3 …… k
k	Number of messages to be forwarded by node i
k_i	Number of messages to be forwarded by node i
L	Lowest layer order
L_1	Number of nodes in the network Layer-One
L_i	Number of nodes in the network layer-i
l_i	Layer order for the WSN layer which contain node i
m	Maximum number of Primary Disjoined Routes for a node
M	Maximum number of Primary Disjoined Routes for the network
N	Total number of nodes in the network except the sink
$\tilde{n}_j$	Route Normalized Weight for route j
p_i	Weight assigned to route i
p_j	Weight assigned to route j

R	Network Routing Efficiency
r_f	Network Routing Factor
r_i	Routing Efficiency for a node i
$R_i(k)$	Normalized Residual Workload of route i right before the routing decision for the k-th message is made
$R_j(k_i)$	Normalized Residual Workload of route j for node i right before the routing decision for the k_i-th message has been made
$S(j)$	Size of the j-th message
s_f	Network Size Factor
ß_i	Network Hops Factor for node i
T	Total number of routes discovered by all nodes
t_i	Total number of routes discovered by node i
$\hat{W}_i (k)$	Actual workloads send on route i
$W_i (k)$	Expected workload (Theoretical workload) to be send on route i right after the routing decision for the k-th message has been made
$\hat{W}_j (k_i -1)$	Actual workloads send on route j right before the routing decision for the k_i-th message has been made
$\hat{W}_j (k_i)$	Actual workloads send on route j
$W_j (k_i)$	Expected workload (Theoretical workload) to be send on route j right after the routing decision for the k_i-th message has been made
X	Number of Primary Disjoined Routes discovered by the Multipath Finding Protocol for the network
x_i	Number of Primary Disjoined Routes discovered by the Multipath Finding Protocol for a node i
β	Network hops factor, it is to define the impact of the route number of

	hops on the weight for route j
$\Delta W_j (k_i)$	Delta workload of route j for node i. It is the difference between the expected workload and the actual workload on route j right before the routing decision for the k_i-th message has been made
ε_j	Energy bottleneck for route j
λ_j	Load bottleneck for route j

Chapter 1: Introduction

1.1. Introduction

In this section, an introduction to multipath routing has been provided. Also, a list of the advantages of using multipath routing has been included.

1.1.1 Multipath Routing in Wireless Sensor Networks

Wireless sensor networks (WSN) are made of a collection of small nodes with sensing, computation and wireless communications capabilities. In general, WSN operates by small and limited battery. Thus, an energy aware routing protocol is an essential design issue to prolong the connectivity and the lifetime of the WSN. A number of nodes in the WSN would work collectively to relay packets from the source node to the destination node when both nodes are out of direct communication range. WSN are randomly deployed with high node density.

In general, there exist several paths between a source and a destination in a WSN with acceptable cost. This is because; every node is connected to more than one other node.

Most of the time, WSN topology at the time of deployment shows a reasonably well-connected network. The topology of the WSN is not predetermined. Even though the sensing nodes are mostly static, the WSN topology would change due to node failure, wireless channels communication failure and the nature of the environment where the WSN are being deployed. It is the task of every sensor node to sense its local environment and sends data of interest back to the sink upon request.

In multipath routing, the traffic is distributed over a number of routes simultaneously. Multi-path routing consists of giving a source node the possibility to use any of several paths to a particular destination at any given time. Multipath routing reduce the over loading of any one node, which result in preventing that node running out of battery. By taking advantage of the connectivity redundancy in the WSN, the source node would have a database of all available paths to a particular destination (the sink) at all times.

Maxemchuk is the first to introduce Multipath routing in 1975 [MAX75]. Multipath routing was referred to as dispersity routing by Maxemchuk at that time. Multipath Routing/Dispersity Routing would provide load balancing, reliability enhancing and fault handling in packet switching network by spreading the traffic from the source in space rather than in time. Hence, Multipath routing would improve performance and efficiency in a WSN by aggregating resources. This can be achieved by dispersion of traffic over the multiple paths available for the source node.

The latest contribution to multipath routing was made by Gonzalez, Villasenor-Gonzalez and Sanchez in 2007 [GAL07]. In there work, a framework for finding the multiple routes from each node to the sink was introduced. Also, a framework for splitting traffic on all available routes was introduced.

In multipath routing, the traffic is spread over multiple paths and transmitted in parallel by the source node through the network. The multipath routing could be used alternately or concurrently. Multipath routing helps in utilizing network resources to full potential and to equalize the traffic load.

1.1.2 Advantages of Multipath Routing in Wireless Sensor Networks

Multipath routing advantages over single path routing [GAL07]:

- Smoothing out the traffic
- Alleviating the network congestion
- Improving the fault tolerance
- Load balancing
- Supporting quality of service (QoS)
- Reduce the end-to-end delay
- Improves reliability and self-healing: reliability is determined by the probability that a message generated by one node in the network would reach it intended destination
- Reduce the frequency of route discoveries
- Improve the network security
- Enhancing the privacy of the information being sent
- Extending the lifetime of the system in wireless sensor networks by distributing more homogeneously the power consumption among its nodes

1.2 Motivations

WSN are a combination of sensing nodes with wireless capabilities. As far as a node in a WSN is concerned, all data communication are directed to or received from a more powerful super node called the sink node. The nods depend on each other to communicate with the sink node, since the short radio range does not allow each node to communicate directly with the sink node. 2 AAA disposable batteries power the nods. Thus, it is crucial to develop routing protocols that would maximize the network energy resources to prolong the connectivity between the network nodes. As a result, the network lifetime would increase. Hence, this would prevent premature failure of nodes or of the network.

1.3 Thesis Objective

The main objective of this thesis is to investigate the challenges of applying multipath routing in WSNs. The first challenge is developing a protocol for finding the multiple paths with desired properties. The second challenge is designing a protocol for splitting the traffic among the multiple paths, which is the traffic distribution. The third problem is prolonging the WSN lifetime and connectivity by optimizing the network over all power usage. The fourth issue is QoS in terms of message delay time. The Delay time is measured when the sink receives messages. The focus of this thesis would be on all four challenges.

1.4 Thesis Contributions

In this thesis, contributions toward solving the four challenges involved in the multipath routing on WSN have been provided. The first contribution is an improvement to the multipath finding protocol over the one introduced in [GAL07]. The second contribution is an improvement to the traffic splitting protocol over the one introduced in [GAL07]. The third contribution is the Hybrid routing protocol, which combines the concepts of the Source and Diffusion Routing technique in one routing protocol for WSN. Also, algorithms for the Hybrid, Source and Diffusion Routing Protocol have been developed. The fourth contribution is a definition for the types of broadcasts in WSN. The fifth contribution is a definition for the WSN Layers. The sixth contribution is a definition for the types of paths in WSN. The seventh contribution is a definition for the Multipath Finding Protocol Efficiency (MFPE). The eighth contribution is a definition for the Network Routing Efficiency (NRE). The ninth contribution is a definition for the WSN Factors. All the defined parameters have been used in this thesis to compare between the effects that different protocol would have on a WSN.

1.5 Thesis Outline

Chapter 2 provides background information for multipath routing in WSNs. Along with a survey of the literature and a summary of earlier research work. Chapter 3 describes the multipath finding protocol used and defines the changes that have been made to the protocol. Also, the definitions for the types of broadcasts, WSN layers and types of paths in WSN have been provided. Chapter 4 provides the adjustments and modification made to the Traffic Splitting Protocol (TSP) used and the related previous work. Chapter 5 presents the Hybrid Routing Protocol and explains its framework. Also, a background and the algorithm are provided for Source and Diffusion Routing Protocol. Chapter 6 presents the performance evaluation based on simulation. Appendix A shows a graphical representation of the routes discovered using the Multipath Finding Protocol for the WSN used for testing. Appendix B shows the statistics for the network characteristics when Type-four broadcast is used in Phase-one of the Multipath Finding Protocol. Chapter 7 concludes the thesis and recommends future research work.

Chapter 2: State of the Art Multipath Routing in WSN

2.1. Introduction

The optimal single path routing protocols tries to construct a single energy-efficient path between a source and a destination node, typically by defining the “cost” of a link. Focusing on choosing the best possible path, however, limits the opportunities for making trade-offs between link capacity and energy consumption. Extending the focus to multiple paths and balancing the energy consumption across multiple paths become an option worthwhile exploring. Moreover, multiple paths provide redundancy in that they can serve as “hot standbys” to quickly switch to when a node or a link fails.

Multipath Routing Protocols construct several paths between a given source and a destination node. The basic goal is to find several paths that do not have either links or nodes in common (apart from the source and destination node, of course). Some basic references on finding multiple paths in general networks are [LEE99], [OGI89] and [SID91]. Once the paths have been established by each node in the network, the routing protocol can then dynamically decide which path (or even paths) to choose to transmit a message. This can increase the robustness of the message delivery process toward link or node failures.

Applying multipath routing to WSNs is a well-studied problem [AYA93], [BAN96], [LEE01], [NAS02], [NAS99], [PAP02], [PEA00] and [ZHE04]. The objective of multipath routing in WSNs is to reduce the load on the most used routes (the shortest routes) by evenly distributing the traffic load on all routes (longer routes) to even the load on all routes and smooth out the traffic. As a result, the network lifetime would be prolonged.

2.2 Related Previous Work

Previous studies in Multipath Routing Protocols (MRP) introduce the following protocols:

- Alternate Path Routing
- Concurrent Multipath Routing
- Energy Aware Routing
- Source Routing
- Diffusion Routing
- Sequential Assignment Routing
- Energy Efficient Secondary Paths Routing
- Simultaneous Transmissions over Multiple Paths Routing
- Randomly Choosing One of Several Paths Routing

2.2.1 Alternate Path Routing

In Alternate Path Routing Protocol (APRP) [PEA00], each sensing node would keep a database of alternative routes to the sink. The database could contain the complete path to the sink or only the next hope path to the sink. When the primary route fails, the sensing node would select another route as the primary route for its future data forwarding. The set of different paths to the sink could be joined paths or disjoined paths. This protocol was originally intended for mobile ad hoc networks.

2.2.2 Concurrent Multipath Routing

In Concurrent Multipath Routing Protocol (CMRP) [TSI01], the data traffic forwarding would take place over a number of different paths simultaneously. This protocol was developed for mobile ad hoc networks to improve throughput, reliability, load balance and security. A source coding scheme and some redundancy are used as will in correlation with concurrent multipath routing.

2.2.3 Energy Aware Routing

In Energy Aware Routing Protocol (EARP) [SIN98], the goal is to choose the best route to the sink such that the total energy consumed by the network is minimized, by using the shortest path to the sink. In this protocol, a heterogeneous network with different nodes would have different level of power consumption. Also, minimum energy paths would drain out first while other paths would not be used. As a result, early death of a number of nodes is expected as well as network partitioning which would lead to network failure. Emphasize on the use of multipath routing by using different routing path each time a message is to be forwarded would be a solution to this problem. Since, changing the routing path used for message forwarding would increase the network overall lifetime. This protocol was developed for both mobile ad hoc networks and WSN.

2.2.4 Source Routing

In Source Routing Protocol (SRP) [LOU05B] [ALK04], each node keeps a database of different paths to the sink. The source specifies which route each message will take to reach the sink. The message follows the exact route specified by the source node. Since, each message would include the complete path that must be followed to the sink. The route selection seeks to smooth out traffic on the WSN, to optimize link capacity and to extend battery life.

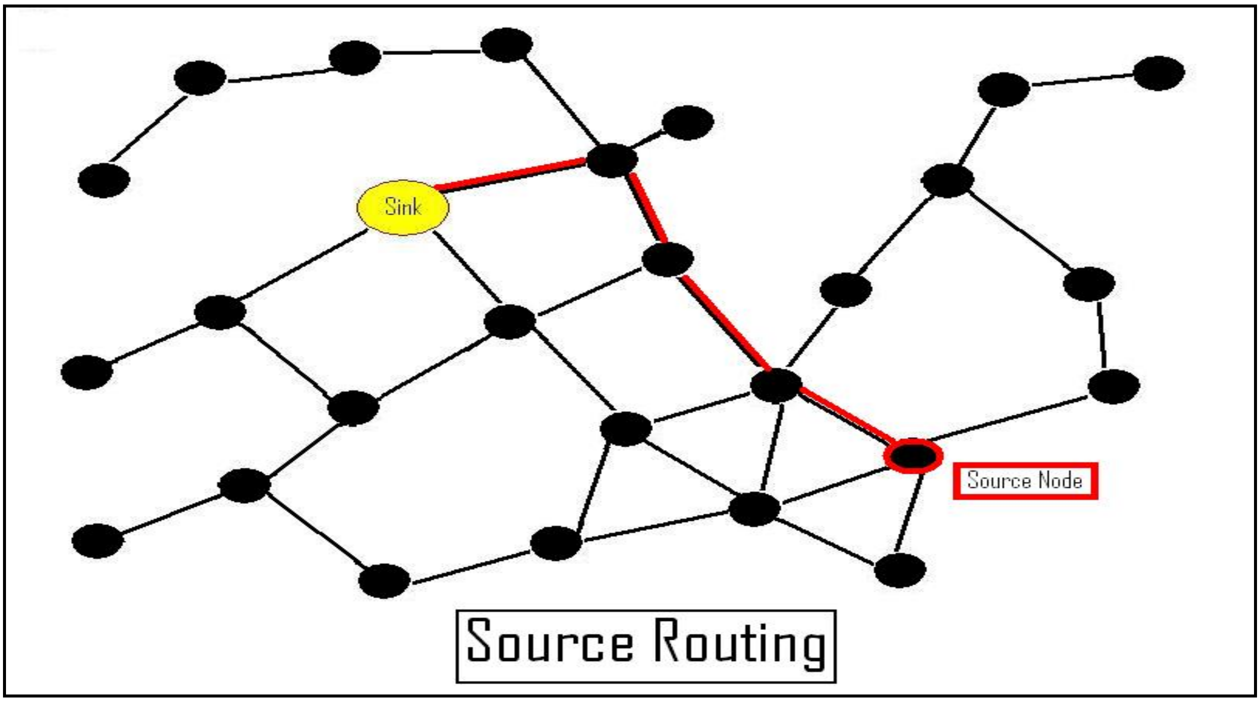


Fig. 2.1: Source Routing Diagram

2.2.5 Diffusion Routing

In Diffusion Routing Protocol (DRP) [MAX75] [ALK04] [LOU05A], each node keep a database of different paths to the sink. For each message to be sent to the sink, the source node will chose only the next node and forward the message to it. The source node will not specify the entire route to the sink. Instead, each node that receives the message will forward it one hop closer to the sink by choosing the next node from one of its known routes. The route selection seeks to smooth out traffic on the WSN, to optimize link capacity and to extend battery life.

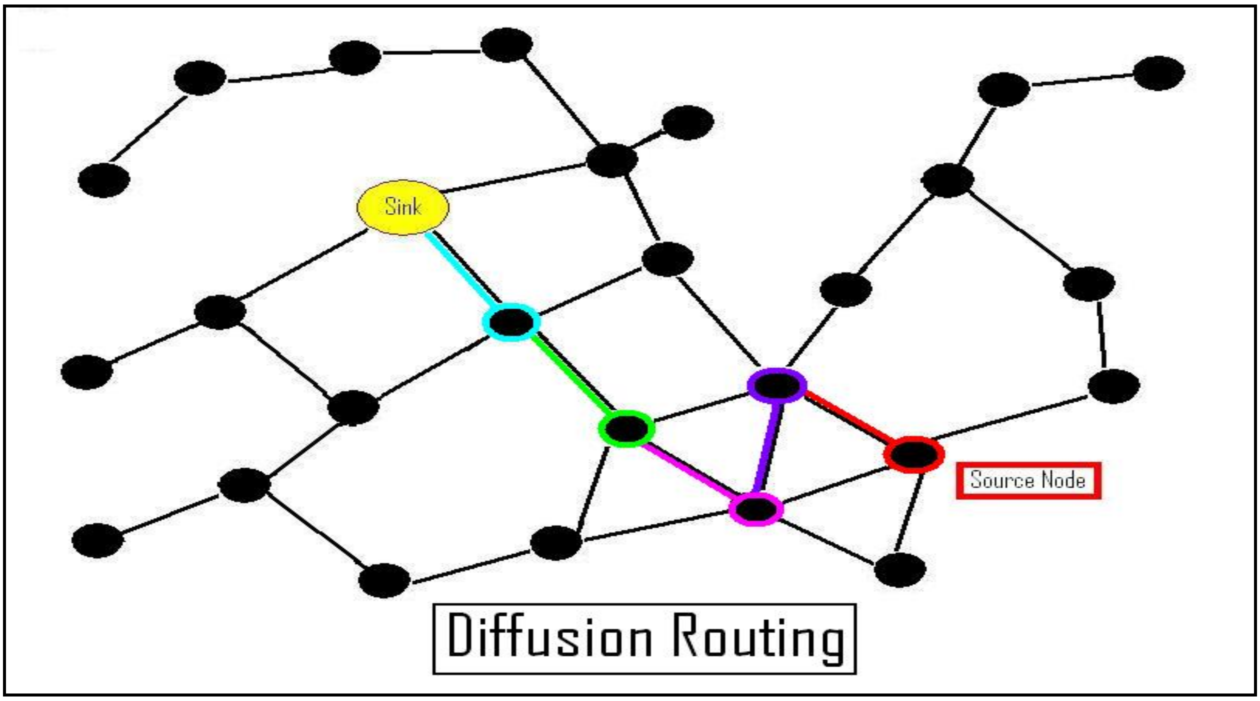


Fig. 2.2: Diffusion Routing Diagram

2.2.6 Sequential Assignment Routing

Computing n-disjoint paths requires about n times more overhead than a single-path routing protocol [SOH00]. The authors of [SOH00] only require paths to use different neighbors of the sink to reduce the multipath finding overhead involved. The Sequential Assignment Routing algorithm achieves this objective by constructing trees outward from each sink neighbor; in the end, most nodes will then be part of several such trees. A packet’s actual path is then selected by the source on the basis of information about the available battery resources along the path and the performance metrics (e.g. delay) of a given path.

2.2.7 Energy Efficient Secondary Paths Routing

When using multiple paths as standby paths, an obvious concern is that of the energy efficiency of Secondary Paths compared to the Optimal Primary Path. The authors of [GAN02] consider how to construct the Secondary Paths from the perspective of the energy efficiency of Secondary Paths compared to the Optimal Primary Path, without worrying about battery capacity or similar metrics along the various paths.

Their first observation is that strictly requiring nodes to be disjoint between the various paths tends to produce rather inefficient secondary paths as large detours will be necessary. To overcome this problem and yet retain the robustness advantages of multiple paths, the authors of [GAN02] suggest the construction of so-called "Braided" Paths (sometimes also called "Meshed" Multipath by the authors of [QIA03]). These Braided Paths are only required to leave out at least one node of the primary path but are free to use other nodes on the primary path. This relaxed disjoint requirement results in paths that can "stay close" to the primary path and are therefore likely to have a similar and close to optimal energy efficiency as the primary path. Fig. 2.3 illustrates these two redundant paths' concepts.

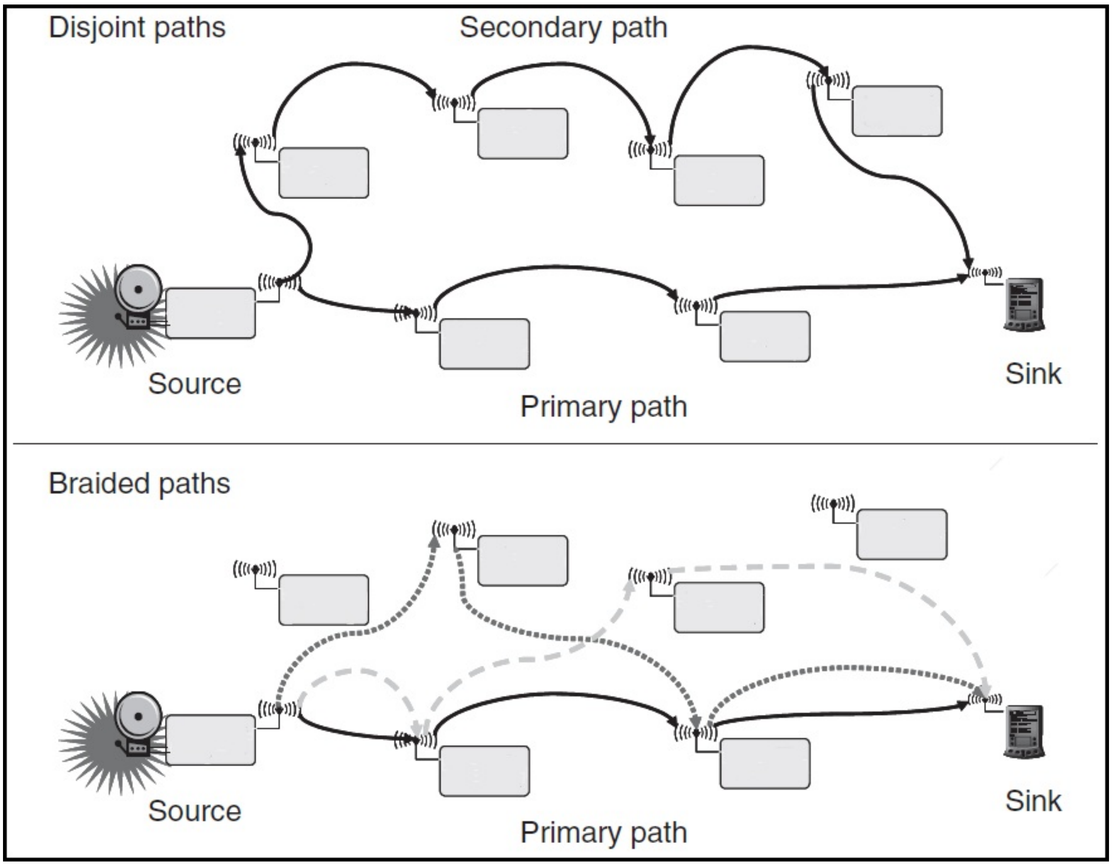


Fig. 2.3: Disjoint and Braided Paths around a Primary Path

Constructing these two different types of redundant paths is simple in a centralized fashion; a distributed construction is described in [GAN02]. For Disjoint Paths, the data sink not only reinforces the primary path via its best neighbor toward the data source but also sends out “Alternate Path” reinforcement to its second-best neighbor (or several such neighbors, for multiple standby paths). This Alternate Path Reinforcement is then forwarded toward the best neighbor that is not already on the Primary Path. For braided paths, each node on the Primary Path (including the sink) sends out such an Alternate Path Reinforcement, which only has to avoid the next upstream node on the Primary Path but is then free to use nodes on the Primary Path.

2.2.8 Simultaneous Transmissions over Multiple Paths Routing

It is conceivable to use all or several of the multiple paths simultaneously to further shorten the time to delivery and to increase the delivery ratio of a given packet. The simplest idea is to assume node-disjoint paths and to send several copies of a given packet over these different paths to the destination. This trades off resource consumption and energy efficiency against packet error rates.

The authors of [QIA03] provide a performance comparison of such packet replication scheme with other multipath schemes. The authors of [DUL03] combine the basic idea of sending packet replicas with splitting a packet and its error correction redundancy over several paths, to be recombined at the receiver. The degree of redundancy and the number of paths can be tuned to the expected error behavior, trading off overhead against residual packet error rate.

2.2.9 Randomly Choosing One of Several Paths Routing

Using paths that are less energy efficient than the optimal path, when maintaining multiple paths, is useful to share the load among all nodes in order to use the available battery capacity in the network better. A way of doing so is described by the authors is [SHA02]. Each node maintains an energy cost estimate for each of its neighbors toward the destination; packets are not routed “away” from their destination. When forwarding a packet, the next hop is randomly chosen proportional to the energy consumption of the path over this neighbor. To the upstream node, the appropriately weighted average of these costs is reported, the harmonic mean of the costs.

This routing approach is extended by the authors of [WIL02] by introducing the notion of altruists. An altruistic node is one that is willing to do more work on behalf of its neighbors, for example, because it has a tethered power supply, such asymmetric nodes can be efficiently exploited by the routing protocol by occasionally broadcasting “altruistic announcements” into the network.

2.3 Routing and topology control

In a clustered Wireless Sensor Network where the topology is based on a dominating set of nodes, the routing problem has to be solved by reducing the network topology. However, it is not clear how information about battery capacity can be taken into account, [CHI97], [HON02], [ASL01], [PEI99], [SIV98] and [HEI00]

2.4 Maximizing Data Flow for Multiple Source/Destination Pairs

The authors of [SRI02] looked at a situation where several sources of data are distributed in the network, each one trying to send as much data to a dedicated sink, using multiple routes. Each node equipped with a utility function to optimize the routes selection. The authors derive a flow control algorithm such that the total utility of the network is maximized before the first node runs out of energy.

2.5 Consider all Costs

Most research tried to find minimum energy cost paths but did not take into account all sources of energy consumption. The authors of [BAN02] argue that costs for retransmissions have to be taken into account as residual error rates over wireless links cannot be neglected. Also, the authors compared paths resulting from local retransmission schemes with end-to-end retransmission schemes.

2.6 Integrate Scheduling and Power Control

The authors of [CRU03] describe a scheme that takes into account link scheduling and power control jointly with the computation of routes to obtain optimal solutions. The result is a relatively complicated optimization problem that minimizes total average power consumption based on traffic requirements for all links. Also, similar approach is taken by the authors of [BER04], who use the results of a power control algorithm as an input to routing algorithms.

2.7 Routing and Link Quality

The authors of [WAN03] advocate a careful selection of actual neighbors using information that the link layer can provide. In their case it was the parents for a routing tree toward a data sink. This is to overcome the problems of bad link quality within the network. While most routing protocols are formulated in a theoretical graph manner, it is often by no means clear which nodes are connected by a link. A related issue is the quality of the underlying links. Links fluctuate in reliability and can have relatively high packet error rates. Using flooding-based protocols over such links can result in routing tables where nodes are considered to be neighbors only because a flooding packet happened to go through despite actual bad link quality.

2.8 Routing and Lifetime Guarantees

The authors of [SAF03A] and [SAF03B] attempt to provide guarantees on the lifetime of the network. The determined routes influence the lifetime of the network. The Wireless Sensor Network life time could be guaranteed in terms of guaranteeing data through put or first node to die or first segmentation of the network.

2.9 Routing for One-Shot Queries

The author of [HEL04] proposes a scheme that handles such one-shot queries without recurring to location knowledge. The intuition behind it is that nodes know about their R-hop neighborhood; for queries outside this immediate neighborhood, so-called contact nodes are involved. These nodes are selected by nodes at the border of given vicinity when the query has not been satisfied locally.

A query is to be routed to the place where it can be evaluated (destination node) and then route the answer back to the place where the query originated (originated node). Queries can be categorized depending on the dynamics of the network. A “one-shot queries” is when the structure of the network has changed sufficiently by the next query so that any topology information that the first query might have acquired is already outdated.

Chapter 3: Multipath Finding Protocol

3.1. Introduction

As it is the case in WSN, the sensing nodes would not communicate among each other. The nodes in the network are to sense the environment. Also, upon request, each node would forward sensing data to a centralized super node called the sink. Thus, the only routes to be found are the routes between every node and the sink. The relationship between the sink and the other nodes in the WSN is N-to-1.

The Multipath Finding Protocol consists of four phases. Phase one is the broadcast phase. Phase two is the routes sharing phase. Phase three is routes counting phase. Phase four is critical nodes finding phase.

3.2 Multipath Finding Protocol

The Multipath Finding Protocol used in this thesis has four phases. The first phase is Broadcast Phase (Phase-one). The second phase is Routes Sharing Phase (Phase-two). The third phase is Routes Counting Phase (Phase-three). The fourth phase is Critical Routes Finding Phase (Phase-four).

3.2.1 Broadcast Phase (Phase-one)

Lou [LOU05A] has introduced the broadcast phase. For the multipath finding process in which, the sink periodically broadcast a route-update message. The goal of this phase is to identify the route from each node to the sink. As the broadcast reach the nodes in the sink communication range, the receiver nodes would rebroadcast the message to the nodes within its communication range. This process would continue until all nodes in the network receive the broadcast.

In more details, the sink broadcasts a route update message to the nearby nodes. The nodes receiving the update message from the sink would be identified as branches. Each branch node would modify the update message by indicating itself as the branch, adding its node ID to the path to the sink filed in the message, incrementing the cost by 1 and identifying itself as the source of the update message. The branch nodes then rebroadcast the update message to its neighboring nodes.

When a non-branch node receives the update message, it would modify the update message by adding its node ID to the path to the sink filed in the message, incrementing the cost by 1 and identifying itself as the source of the update message. Then, the receiver node rebroadcast the update message again to its neighboring nodes. This is to be done recursively until all nodes in the WSN receive the update message.

Each node receives the broadcast for the first time would mark the node it receive the update message from as its parent and the branch it receive the update message from as its branch. When the same node receives the same update message more than one time, the receiving node would mark the sending node as a descendant or as a cousin depending on the branch and path identified in the message. If the branch ID in the message were different from the receiver node branch, then the sender node would be marked as cousin by the receiving node.

The parent node and the cousin nodes represent the different paths each node can use to reach the sink. The receiver node would add the path found in the path field in the message to the receiver node routing table.

3.2.2 Routes Sharing Phase (Phase-two)

The first and second phases form the Multipath Finding Protocol proposed by Luo [LOU05A]. In this phase, each node would independently broadcast messages to share the alternative routes to the sink found by the node with its neighboring nodes. The receiver node would discard the message if the receiver node ID were on the path in the received message. Up to this point, each node would discover all disjoint minimum cost routes available to the sink.

3.2.3 Routes Counting Phase (Phase-three)

The authors of [GAL07] have introduced this phase in 2007 to be added to Lou two phase's Multipath Finding Protocol [LOU05A] as phase three. Phase three is to start after finding all the multipath routes to the sink by each node in the WSN as described earlier in phase one and two. In this phase, each node would independently send a message to the sink through each of the routes discovered by the node. The path field in the message sent would contain the whole path from the node to the sink. Each time a node receive this message, it would increment a local-on-node counter to reflect how many routes does go through the node. Then, the node would forward the message to the next node on the path. Eventually, when the message reaches the sink, the sink would add the path in the message to a probe table. The probe table is where the sink keeps all the routes received in phase three type messages.

The goal of this phase is to get every node to know how many routes go through it to connect other nodes in the network to the sink. The number of routes going through a node is different from the number of routes the node discovered to the sink. The number of routes going through a node reflects how dependent other nodes in the network are on the node to forward messages to the sink. Also, it reflects the demands faced by the node in terms of how often it would receive and forward messages for other nodes.

3.2.4 Critical Routes Finding Phase (Phase-four)

The authors of [GAL07] have also introduced this phase to be added to Lou [LOU05A] two phase's Multipath Finding Protocol as phase four. This phase is the final stage in the multipath finding protocol, combined with the earlier phase one, two and three. In this phase, the sink would send a message through every route stored in the probe table. The path field in the message would contain the reverse path of the one in the probe table. The message would be updated every time a node on the path received it, up to the message final destination. Every receiving node would modify the message to indicate the minimum energy level and the maximum number of routes going through the bottleneck node on the path. When the message reach it is final destination, the final destination node would assign a weight to the path.

The goal of this phase is to find the highest number of routes going through a node for each path and the lowest level of a node power for the same path. The value for the highest number of routes going through a node would be saved in the load bottle nick field in the phase four messages sent by the sink. The lowest level of a node power would be saved in the energy bottle nick field in the same message. All nodes receiving the phase four messages would compare the value of the load bottle nick and energy bottle nick fields in the message with its own values of number of routes going through and power level. The receiver node would make changes to the values of either one of the message fields or both as to reflect the correct values for the route.

The message would eventually reach the final receiving node, which would use the values stored in the load bottle nick field and the energy bottle nick field in the message to calculate a weight for the route. The weight of a route would be used to divide the node traffic on all the routes discovered in the most efficient way to extend the life of the network and to proportionally divide the load of each node on all of its routes. This would be expanded on in more details in the next chapter, Chapter 4.

The goal of phase three and phase four is to gather information about the network to assign weights to all routes to the sink discovered by each node. As it is the case for phase one and phase two, performing phase three and four more than one time would only lead to power consumptions without any performance improvements as all the routes in the network are static.

3.3 Types of Broadcasts

One of the contributions of this thesis is categorizing broadcasting into four types. Broadcasting is used in the Broadcast Phase (Phase-one) of the Multipath Finding Protocol. The four types of broadcasting are Type-one broadcast, Type-two broadcast, Type-three broadcast and Type-four broadcast.

3.3.1 Type-one Broadcast

In type-one broadcast, every broadcast message received from one neighboring node is to be rebroadcast to all neighboring nodes. When one message is to be transmitted that way, it would keep circulating in the network forever or until all nodes are out of power. This would cause massive depletion of the over all network resources.

The only way to stop the message from circulating the network over and over again is to put a timer or a counter on it. So, after a specific time or number of broadcasts, the message would not be rebroadcast any more. In this case, no mechanism to remember previous received broadcast by a node is needed.

The problem with this type of broadcasting, it have no embedded mechanism to end the rebroadcast. As a result, it consume a large amount of the over all network power. Also, it results in a large number of unwanted paths when used for phase-one of the Multipath Finding Protocol in a WSN. An example of unwanted paths would be duplicated, circular, and long paths. The types of paths would be explained in more details in the next section of this chapter. The vast majority of the paths discovered by type-one broadcast are far from being optimum or practical or usable.

Another problem of using this type of broadcasting in phase-one of the Multipath Finding Protocol is the over head burden of processing such large number of paths in the remaining phase two, three and four of the protocol.

Paths discovered through type one broadcast would need considerable processing to delete unwanted paths. So, the WSN would consume a large amount of valuable resources in terms of WSN time and power to discover a large number of routes that would not be used and deleted. For that reason, this type of broadcasting was not considered for the purpose of Phase-one of the multipath finding protocol.

3.3.2 Type-two Broadcast

In type-two broadcast, every broadcast message received by a node is to be rebroadcast to all neighboring nodes as long as the receiver node ID is not in the path field in the received message. This is the broadcast method used in phase one of the Multipath Finding Protocol by Lou two phase Multipath Finding Protocol [LOU05A] as phase one in the protocol. Also, it is the broadcast method used in phase one of the four phases Multipath Finding Protocol by the authors of [GAL07].

Type-two broadcast is the most comprehensive way to find multipath in WSN. It has an embedded self-terminating mechanism, which is an advantage over type one broadcast. Broadcast termination in type-two broadcast is dependent on the network topology. So, the message would not be rebroadcast depending on the path each different copies of the message traveled through the network, a variable dynamic number of hops. This is in comparison to the type-one broadcast preset static maximum number of hops value for each copy of the message. Type-two broadcast is more power-efficient and provide more paths when used in phase-one of the Multipath Finding Protocol compared to using type-one broadcast in phase one of the multipath finding protocol.

In the same time, type-two broadcast shares all the other characteristics of type one broadcast. A node does not need a mechanism to remember previous received broadcast. It consume a large amount of the over all network power. When used for multipath finding in a WSN, it results in a large number of duplicated, circular, and long paths. The paths discovered by this way are far from being optimum or practical or usable. The paths collected need to be refined to delete duplicated, circular and long paths [GAL07]. Another problem of using this type of broadcasting in phase-one of the Multipath Finding Protocol is the over head burden of processing such large number of paths in the remaining phase two, three and four of the protocol.

Paths discovered through type-two broadcast would need considerable processing to delete unwanted paths. So, the WSN would consume a large amount of valuable resources in terms of WSN time and power to discover a large number of routes that would not be used and deleted. Even though, this type of broadcasting was considered for the purpose of Phase-one of the multipath finding protocol. This is to compare the results obtained by using type-two broadcast to other results obtained by using type-three and type-four broadcast.

3.3.3 Type-three Broadcast

In type-three broadcast, the node internal memory would be used to keep record of the last broadcast received. This is done by remembering the last broadcast message received ID, source node ID and the sender node ID. In the case of phase one multipath finding protocol, the source node is always the sink. This is to be done for each time the receiver node receives a Phase-one type broadcast message.

Once a node receives a broadcast message of type-three broadcast, it would compare the message ID field and the source node ID field in the message to the ones in the internal memory. If the message was not received before, the message ID field and the source node ID field in the message would be saved to memory, the sender nodes list in the node internal memory would be reseated and the message would be rebroadcast to neighboring nodes. If the message had been received before, the receiver node would compare the sender node ID field in the message with the sender nodes ID list in the node internal memory. If a message were not received from the particular sender node, the message would be rebroadcast to neighboring nodes and the sender node ID would be added to the sender nodes ID list of which the receiver node already received the message from. If the message were received before from the same sender then, the message would be discarded and would not be rebroadcast.

This means each node would broadcast the message as many times as the number of nodes it is connected to. Also, it would receive the message as many times as each of its neighboring nodes are connected to other nodes. As a result of broadcasting the massage at the first time received from a sender node, the shortest paths are promoted through the network. Also, Parallel paths would be discovered as well. In the same time, no duplicated or circular or long paths would be discovered or promoted.

This type of broadcasting was considered for the purpose of Phase-one of the multipath finding protocol. This is to compare the results obtained by using type-three broadcast to other results obtained by using type-two and type-four broadcast.

3.3.4 Type-four Broadcast

In type-four broadcast, the node internal memory would be used to keep record of the last broadcast received. This is done by remembering the last broadcast message received ID and its source node ID. In the case of phase one multipath finding protocol, the source node is always the sink. In comparison to type-three broadcast no internal memory is needed to save a list of the broadcast message sender nodes ID.

Once a node receives a broadcast message of type-four broadcast, it would compare the message ID field and the source node ID field in the message to the ones in the internal memory. If the message was not received before, the message ID field and the source node ID field in the message would be saved to the receiver node internal memory and the message would be rebroadcast to neighboring nodes. If the message had been received before, the message would be discarded and would not be rebroadcast.

This means each node would rebroadcast the message only once. Also, it would receive the message as many times as the number of nodes it is connected to. As a result of broadcasting the massage at the first time received from a sender node, the shortest paths are promoted through the network. Also, Parallel paths would be discovered as well. But, it is not as often as it is the case in type-three broadcast. This is due to the fewer number of rebroadcasts made by each node in Phase-one of the

Multipath Finding Protocol when type-four broadcast is used compared to using type-three broadcast. In the same time, no duplicated or circular or long paths would be discovered or promoted.

This type of broadcasting was considered for the purpose of Phase-one of the multipath finding protocol. This is to compare the results obtained by using type-four broadcast to other results obtained by using type-two and type-three broadcast.

3.4 Wireless Sensor Network Layers

The nodes in WSN could be divided into layers based on the shortest distance from each node to the sink. The way to get the shortest distance from a node to the sink is by sending a broadcast message from the sink to all nodes. The message would have a number of hops field. This field would be set to one by the sink in the initial broadcast. As a node receives the broadcast for the first time, it would read the number of hops field in the message and that would be the node shortest distance to the sink. The receiver node is to increments the number of hops field in the received message by 1. The receiver node is to rebroadcast the message to its neighboring nodes when it is the first time for the message to be received by the node. The node is to discard the message otherwise without rubricating.

The layers would form a hierarchy with the sink at the top of the hierarchy. The higher layers would be at the top of the hierarchy and the lower or deeper layers at the bottom. Only the sink would form the highest layer and it would be layer zero. Layer one would follow layer zero in the hierarchy. Layer one would contain nodes able to receive and send messages to the sink directly, the nodes one hop away from the sink. Layer two would follow layer one and would contain of the nodes that are two hops away from the sink. The lowest layer or the deepest layer would contain the nodes that are farthest the most from the sink, the nodes that have the largest number of hops to the sink.

Every layer has a layer order. The layer order is the distance in hops from the nodes in the layer to the sink. So, Layer-One would have a layer order of one and Layer-Two would have a layer order of 2 and so on.

The network nodes in Layer–One are the network nodes that handle the most traffic. This is because of there position next to the sink where all routes end. As a result, they are the first nodes in the network to go out of power. For that reason, it is important to divides all routes of the network nodes evenly between the network Layer-One nodes to extend the network over all lifetime and connectivity.

Further more, uneven division of the network routes between the network Layer-One nodes would negatively affect the network in two ways. First, it would speed up the power depletion of the node with the larger number of routes going through it to the sink. This would cause the node to be nonfunctional and fragment the network after disabling all the routes that goes through the nonfunctional node. Second negative effect, a larger section of the network would be affected since the nonfunctional node handles larger number of routes than the other nodes in the network Layer-One.

WSNs Layers is one of the contributions made in this thesis.

3.5 Types of Paths in WSN

Categorizing the paths in Wireless Sensor Networks is one of the contributions made in this thesis. The type of paths discovered by the Multipath Finding Protocol in a Wireless Sensor Network could be categorized into one of nine types of paths. The first type is Primary Path (PP). The second type is Non-Primary Path (NPP). The third type is Disjoined Path (DP). The fourth type is Primary Disjoined Path (PDP). The fifth type is Joined Path (JP). The sixth type is Parallel Path (PLP). The seventh type is Circular Path (CP). The eighth type is Long Path (LP). The ninth type is Duplicated Path (DLP).

3.5.1 Primary Path

The primary path is the shortest path between a source node and a destination node. The message would move from a node to another node of a higher layer on the primary route only (shortest route). This mans, the message get closer to the sink as it moves from one node to another. This would continue until the message eventually reaches the sink.

3.5.2 Non-primary Path

Non-primary path or otherwise called alternative path is any path that would connect the source node to the destination node without being the shortest path between the two nodes.

When a node uses a non-primary path, the message would be sent to nodes of the same or lower layers before it makes its way up the network hierarchy again to reach the sink. It is important to point out that, once the message travailed from any layer to a higher layer, it should move up the network hierarchy to reach the sink. This is to avoid circular paths. The only reason for a node to be allowed to send its messages to a lower layer node is to use a different last before sink node than the one the primary path uses (a different network Layer-One node other than the one the primary route uses).

It is undesirable for a node to use nodes of lower layers in delivering a massage to the sink. This is because; the message would travel farther away from the sink before it gets closer to the sink. This would cause longer delays and more power consumption of the over all network per message delivered to the sink. In the same time, to extend the over all network lifetime and connectivity, alternative non-primary routes are to be used in addition to the primary route. For that reason, longer paths through lower layers nodes are a must to gain access to the sink through a different Layer-One-Node other than the one the primary route uses.

3.5.3 Disjoined Paths

Any two different paths between the same source and destination nodes would be recognized as disjoined paths when the very last nodes before the sink on both paths are different (the network Layer-One nodes on both paths are different).

3.5.4 Primary Disjoined Paths

Using nodes of lower network layers to forward message to the sink is undesirable, but it is a must to reach the sink through each of the Layer-One nodes. So, it is to be kept to minimum. There for, the routes that would provide the most variety of routes to the sink yet the shortest distance are the ones to be found and used for message forwarding. Such routes are called primary disjoined paths or primary disjoined routes.

Primary disjoined paths are the shortest routes that go through each of the nodes in the network Layer-One nodes. The routes that fit the above definition would be called the primary disjoined paths or routes. The primary route, which is the shortest path to the sink, would be one of the routes in the primary disjoined routes.

For every network, the maximum optimum number of routes is the set of Primary Disjoined Routes that goes through all Layer-One nodes. Also, for every node and for the network this set of routes could be calculated and roughly defined. The number of nodes in Layer-One would limit the maximum number of the Primary Disjoined Routes for every node, Eq. 3.1. Multiplying the maximum number of Primary Disjoined Routes by the number of nodes in the network would give the maximum number of Primary Disjoined Routes for the network, Eq. 3.2.

$m = L_1$ Eq. 3.1

$M = m * N$ Eq. 3.2

Where: m is Maximum number of Primary Disjoined Routes for a node

L_1 is Number of nodes in the network Layer-One

M is Maximum number of Primary Disjoined Routes for the network

N is the total number of nodes in the network except the sink

The Multipath Finding Protocol Efficiency for a node could be calculated as the number of Primary Disjoined Routes discovered by the Multipath Finding Protocol divided by the maximum number of Primary Disjoined Routes for the node multiplied by 100, Eq. 3.3. In the same way, the Multipath Finding Protocol Efficiency for the network could be calculated as the number of Primary Disjoined Routes discovered by the Multipath Finding Protocol for the network divided by the maximum number of Primary Disjoined Routes for the network multiplied by 100, Eq. 3.4. Also, it could be calculated as the sum of all individual Multipath Finding Protocol efficiencies for all nodes divided by the number of nodes, Eq. 3.5.

$$e_i = \frac{x_i}{m} * 100 \qquad \text{Eq. 3.3}$$

$$E = \frac{X}{M} * 100 \qquad \text{Eq. 3.4}$$

$$E = \frac{\sum_{i=0}^{i=N} e_i}{N} * 100 \qquad \text{Eq. 3.5}$$

Where: e_i is Multipath Finding Protocol Efficiency for a node i

x_i is number of Primary Disjoined Routes discovered by the Multipath Finding Protocol for a node i

E is Multipath Finding Protocol Efficiency for the network

X is number of Primary Disjoined Routes discovered by the Multipath Finding Protocol for the network

The Network Routing Efficiency for a node could be calculated as the number of Primary Disjoined Routes discovered by the node divided by the total number of routes discovered by the node multiplied by 100, Eq. 3.6. In the same way, the Network Routing Efficiency could be calculated as the number of Primary Disjoined Routes discovered by all nodes divided by the total number of routes discovered by all nodes multiplied by 100, Eq. 3.7. Also, it could be calculated as the sum of all individual network routing efficiencies for each node divided by the number of nodes, Eq. 3.8.

$$r_i = \frac{x_i}{t_i} * 100 \qquad \text{Eq. 3.6}$$

$$R = \frac{X}{T} * 100 \qquad \text{Eq. 3.7}$$

$$R = \frac{\sum_{i=0}^{i=N} r_i}{N} * 100 \qquad \text{Eq. 3.8}$$

Where: r_i is the Routing Efficiency for a node i

t_i is total number of routes discovered by node i

R is the Network Routing Efficiency

T is total number of routes discovered by all nodes

Equation 3.1 to 3.8 provides a mathematical framework to evaluate and grad multipath finding protocols. The mathematical framework provided earlier would be used to evaluate the Multipath Finding Protocol used for WSN simulation.

3.5.5 Joined Paths

Joined paths are any two paths originating at the same node in the network and reach the sink through the same Layer-One node.

The existence of joined paths in the WSN would speed up the power depletion at the Layer-One node where the two joined paths meet. This is because; the originating node would over load the Layer-One node where both attached routes meet. This would cause an uneven distribution of load and speed up the power depletion of the critical Layer-One nodes.

3.5.6 Parallel Paths

Parallel paths are any two paths where both paths share the same route for the most part between a source and destination node except where both paths branch out and then branch back in. the parallel section of the path could be at the source node or the destination node or any where in between. The best-case scenario for parallel paths is for the parallel path with the longer number of hops to be deleted and for the one with the smaller number of hops to be kept. Yet, if the parallel section of the path happens at the lower layers, it would be less significant on the performance of the network compared to a higher network layer.

3.5.7 Circular Paths

In circular paths, the message would go through any one node more than once before it reach the destination node (the sink).

3.5.8 Long Paths

The longest acceptable path in a WSN or an Ad-hoc network would have a number of hops equals to subtracting 1 from twice the order of the lowest layer in the network. Any path that would have a larger number of hops is to be discarded and deleted from the node routing table. Long paths would only deteriorate the quality of service of the network by causing longer delays and depletes the network over-all power.

$$H = (2 * L) - 1 \qquad \text{Eq. 3.9}$$

Where: H is Max. No. Of hops for a path

L is lowest layer order

3.5.9 Duplicated Paths

In the case of duplicated paths, the same source node would discover the same route twice. Both routes would exactly follow the same path from the source node to the destination node. In the same time, both routes would be independent of each other and would be considered by the source node as different routes. This would over load the traffic on the duplicated route. Therefore, it would cause uneven distribution of the node’s traffic on its discovered routes. A source node discovers this type of routes when type-one broadcast are used for phase-one of the Multipath finding protocol.

Chapter 4: Traffic Splitting Protocol

4.1. Introduction

As mentioned earlier in chapter 3, in phase-four of the Multipath finding protocol, a message would be sent by the sink through each of the routes stored in the probe table. Phase-four of the Multipath Finding Protocol would find the lowest level of a node power and the highest number of routes going through a node for each of the routes. The value for the highest number of routes going through a node would be saved in the load bottle nick field in Phase-four messages. In the same time, the lowest level of a node power would be saved in the energy bottle nick field. Any node receive the phase four messages would compare the value of the load bottle nick and energy bottle nick fields in the message with its own values of number of routes going through and power level. A node would make changes to both fields as necessary. As the phase-four messages reach the final receiving node, the Traffic splitting protocol would start.

4.2 Wireless Sensor Network Factors

Categorizing the factors affecting routing in Wireless Sensor Networks is one of the contributions made in this thesis. The Wireless Sensor Network Factors could be categorized into four factors. The first factor is Network Size Factor (NSF). The second factor is Network Routing Factor (NRF). The third factor is Network Connectivity Factor (NCF). The fourth factor is Network Hops Factor (NHF).

4.2.1 Network Size Factor

Network Size Factor is the average number of hops from all nodes to the sink.

$$s_f = \frac{\sum_{i=1}^{i=L} (i * L_i)}{N} \qquad \text{Eq. 4.1}$$

Where: s_f is Network Size Factor

L is lowest layer order

L_i is Number of nodes in the network layer-i

N is the total number of nodes in the network except the sink

4.2.2 Network Routing Factor

Network Routing Factor is the average number of routes to the sink discovered per node.

$$r_f = \frac{T}{N} \qquad \text{Eq. 4.2}$$

$$r_f = \frac{\sum_{i=1}^{i=N} t_i}{N} \qquad \text{Eq. 4.3}$$

Where: r_f is Network Routing Factor

t_i is total number of routes discovered by node i

T is total number of routes discovered by all nodes

N is the total number of nodes in the network except the sink

4.2.3 Network Connectivity Factor

Network Connectivity Factor is the average number of node connected to a node in the network.

$$c_f = \frac{\sum_{i=1}^{i=N} c_i}{N} \qquad \text{Eq. 4.4}$$

Where: c_f is Network Connectivity Factor

c_i is the number of nodes connected to node i

N is the total number of nodes in the network except the sink

4.2.4 Network Hops Factor

Networks Hops Factor, ß, defines the impact of the number of hopes on the weight assigned to a route. As ß get smaller, the weight assigned to a route would get bigger. This means, longer routes would be encouraged. As ß get bigger, weight assigned to a route would get smaller. This means, longer routes would be discouraged. ß takes values between 0 and 1. ß were introduced in [GAL07], but no mathematical framework to calculate its numerical value was provided.

In this thesis, a mathematical framework to calculate the value of ß is provided as follows:

$$ß = \frac{1}{3} \left[\frac{s_f}{(s_f + 1)} + \frac{r_f}{(r_f + 1)} + \frac{c_f}{(c_f + 1)} \right] \qquad \text{Eq. 4.5}$$

The rational behind Eq. 4.5, the numerical value for ß would increase as the numerical value of hops to sink or routes to sink or nodes connected to increases. This means, routes with long paths and large hops to sink values would be discouraged. In the same way, the numerical value for ß would decrease as the numerical value of hops to sink or routes to sink or nodes connected to decreases. This means, routes with long paths and large hops to sink values would be encouraged. The numerical value for ß provided in Eq. 4.5 is an average for all the nodes across the WSN. Thus, another way to calculate ß is as follows:

$$ß = \frac{\sum_{i=1}^{i=N} ß_i}{N} \qquad \text{Eq. 4.6}$$

$$ß_i = \frac{1}{3}\left[\frac{l_i}{(l_i + 1)} + \frac{t_i}{(t_i + 1)} + \frac{c_i}{(c_i + 1)}\right] \qquad \text{Eq. 4.7}$$

Where: $ß_i$ is the Network Hops Factor for node i

N is the total number of nodes in the network except the sink

t_i is total number of routes discovered by node i

c_i is the number of nodes connected to node i

l_i is the layer order for the WSN layer which contain node i

The significance of Eq. 4.7, it provides a way to calculate a value for $ß_i$ that is unique and specific for each node. The data needed to calculate a node specific $ß_i$ is local data for each node. The advantage of having a way for each node to calculate its Network

Hop Factor $ß_i$ means each node can adjust its Routes Weight according to its specific conditions.

4.3 Traffic Splitting Protocol

When multipath routing is used in WSNs, each node would assign a weight to each route discovered to the sink. The weight reflects the route ability to delivers messages from that particular node to the sink. The weight, the expected (theoretical) and actual workload on each route is used to calculate the Normalized Residual Workload (NRW) for each route between a node and the sink. A node would select the route with the highest Normalized Residual Workload for its next message to the sink.

The Traffic Splitting Protocol (TSP) consists of two methods, the Route Weight Assignment Method (RWAM) and the Load Sharing Method (LSM). The two methods take place one after the other.

Adjustments and modifications made to both methods of the Traffic Splitting Protocol to improve the protocol performance is one of the contributions of this thesis.

4.3.1 Route Weight Assignment Method

The Multipath Finding Protocol would come to an end at each node when the node receives one Multipath Finding Protocol Phase-Four Message for each route discovered. The Route Weight Assignment Method would start at each node individually after the Multipath Finding Protocol comes to an end for the node. In the Route Weight Assignment Method, a weight would be calculated for each route by using the values stored in the load bottle nick field and the energy bottle nick field in the message. The following equation would be used for the Route weight calculation:

$$p_j = \frac{\varepsilon_j}{\lambda_j * (h_j)^{\beta}} \qquad \text{Eq. 4.8}$$

Where: t_i is total number of routes discovered by node i

$j = 1, 2, 3 \ldots\ldots t_i$

p_j is the weight assigned to route j

ε_j is the energy bottleneck for route j

λ_j is the load bottleneck for route j

h_j is the number of hops for route j

β is the Network hops factor, it is to define the impact of the route number of hops on the weight for route j

The rational behind Eq. 4.8, the remaining energy of the route weakest node is proportional to the amount of messages to be forwarded on the route. Also, the number of routes going through the highest load node is inversely proportional to the amount of messages to be forwarded on the route. This is because, the transmission capacity have to be shared among all routes that goes through a node. Also, the number of hops for a message to go all the way from the source node to the destination node is inversely proportional to the amount of messages to be sent on the route.

On one hand, it is encouraged to involve as many nodes as possible in the forwarding of messages to even out the load and energy consumption among all nodes. On the other hand, it is discouraged to use long routes. This is because; the network energy consumed per message delivery increase as the route number of hops increases. Also, the message delay would increase.

The number of hops of a route in a WSN depends on the network topology, the network size and the nodes density. So, the Network Hops Factor β is used in Eq. 4.8. β would serve as exponent for the route number of hops h_j. The rational behind using β in Eq. 4.8 is to count for different WSN lay out when calculating a Route Weight. β determines the impact of the number of hops of a route on the Route Weight.

The weight assigned to a route would reflect the energy bottleneck node power level on the route. So, the route with the node with the least energy would be used the least to send messages to the sink. Also, the weight assigned to a route would reflect the load bottleneck node number of routes going through on that route. So, the route with the node with the most loads would be used the least to send messages to the sink.

After weights are assigned to all routes for each node, the Route Normalized Weight would be calculated for each route. The Route Normalized Weight (RNW) would be calculated by normalizing the Route Weight (RW) for each route discovered by a node. So, the sum of all Routes Weight for each node would be equal to 1.

4.3.2 Load Sharing Method

The load sharing method used is the Generalized Load Sharing method (GLS). Generalized Load Sharing was used by the authors of [LEU06] in 2006 for Packet-Switching Networks. In 2007, the authors of [GAL07] adopted the GLS method for

WSNs in their work. Also, they proposed a modified version to improve its efficiency. In this thesis, a further modification and adjustments to the GLS method aimed at improving its performance and efficiency is one of the contributions that were made in this thesis.

The GLS method start after The Route Normalized Weight (RNW) for each route is calculated, as in the Route Weight Assignment Method discussed above. The value of the Route Normalized Weight for a route means the percentage of the node traffic to be forwarded on the route. Thus, the Route Normalized Weight of a route multiplied by the number of messages to be forwarded by the node would equal the theoretical number of messages to be forwarded on the route.

The adjusted and modified mathematical framework used for GLS method in this thesis is as follows:

$$W_j\,(k_i) = \tilde{n}_j * k_i \qquad \text{Eq. 4.9}$$

$$R_j(k_i) = \frac{W_j\,(k_i) - \hat{W}_j\,(k_i - 1)}{\sum_{j=0}^{t_i} W_j\,(k_i) - \hat{W}_j\,(k_i - 1)} \qquad \text{Eq. 4.10}$$

$$W_j\,(k_i) - \hat{W}_j\,(k_i - 1) = \Delta\, W_j\,(k_i) \qquad \text{Eq. 4.11}$$

Where: t_i is total number of routes discovered by node i

$j = 1, 2, 3 \ldots\ldots t_i$

k_i is the number of messages to be forwarded by node i

$\tilde{n}_j$ is the Route Normalized Weight for route j

$\hat{W}_j$ (k_i) is the actual workloads send on route j

$\hat{W}_j$ $(k_i - 1)$ is the actual workloads send on route j right before the routing decision for the k_i-th message has been made

W_j (k_i) is the Expected workload (Theoretical workload) to be send on route j right after the routing decision for the k_i-th message has been made

Δ W_j (k_i) is the Delta workload of route j for node i. It is the difference between the expected workload and the actual workload on route j right before the routing decision for the k_i-th message has been made

$R_j(k_i)$ is the Normalized Residual Workload of route j for node i right before the routing decision for the k_i-th message has been made

The goal of the GLS method is to minimize the Residual Workload ΔW_j (k_i) on all routes for each node. This would divide the load fairly on all routes. To achieve this goal, each node would select the route with the largest Normalized Residual Workload for forwarding its next message. The Normalized Residual Workload would be used to divide the node traffic on all the routes discovered by the node in the most efficient way. This would extend the lifetime of the network by proportionally dividing the load of each node on all of its routes fairly.

Since the Residual Work is the key factor in the route selection made by a node, it is important to calculate it in the most accurate way to fairly select routes in a frequency relevant to the particular route weight and its ability to forward traffic. Hence, a reduced gape between the expected and the actual workload would result.

The smaller the difference between the expected and the actual workload means a more efficient WSN. In witch, maximizing the overall WSN life span, maximizing the overall network connectivity for longer period of time and minimizing the overall network power consumption are achieved. This would result in a higher overall WSN efficiency, improved performance and longer network life.

The proposed mathematical framework used by the authors of [LEU06] to calculate the Normalized Residual Workload used for GLS method as for Packet-Switching Networks is as follows:

$$R_i(k) = W_i\,(k) - \hat{W}_i\,(k - 1) \qquad \text{Eq. 4.12}$$

The proposed mathematical framework used by the authors of [GAL07] to calculate the Normalized Residual Workload for GLS method for WSN is as follows:

$$W_i\,(k) = p_i \sum_{j_i = 1}^{k} S(j_i) \qquad \text{Eq. 4.13}$$

$$R_i(k) = \frac{W_i\,(k) - \hat{W}_i\,(k - 1)}{p_i} \qquad \text{Eq. 4.14}$$

Where: k is the number of messages to be forwarded by node i

$j_i = 1, 2, 3 \ldots\ldots k$

p_i is the weight assigned to route i

$S(j_i)$ is the size of the j_i-th message

$\hat{W}_i\,(k)$ is the actual workloads send on route i

$W_i\,(k)$ is the Expected workload (Theoretical workload) to be send on route i right after the routing decision for the k-th message has been made

$R_i(k)$ is the Normalized Residual Workload of route i right before the routing decision for the k-th message is made

Chapter 5: Hybrid Routing

5.1. Introduction

Source, Diffusion and Hybrid Routing Protocol is used to provide a multipath routing between a source node and a destination node in a WSN. The destination node is always the sink node. All three routing protocols seek to optimize the resources usage of a WSN. An integration of Source Routing and Diffusion Routing would produce Hybrid Routing. The Hybrid Routing is to combine the advantage of both of the Source and Diffusion Routing in an attempt to gain better optimization of the WSN resources.

5.2 Source Routing

In Source Routing [LOU05] [ALK04], each node keeps a database of different paths to the sink. The source specifies which route each message will take to reach the sink. The message follows the exact route specified by the source node. Since, each message would include the complete path that must be followed to the sink. The route selection seeks to smooth out traffic on the WSN, to optimize link capacity and to extend battery life.

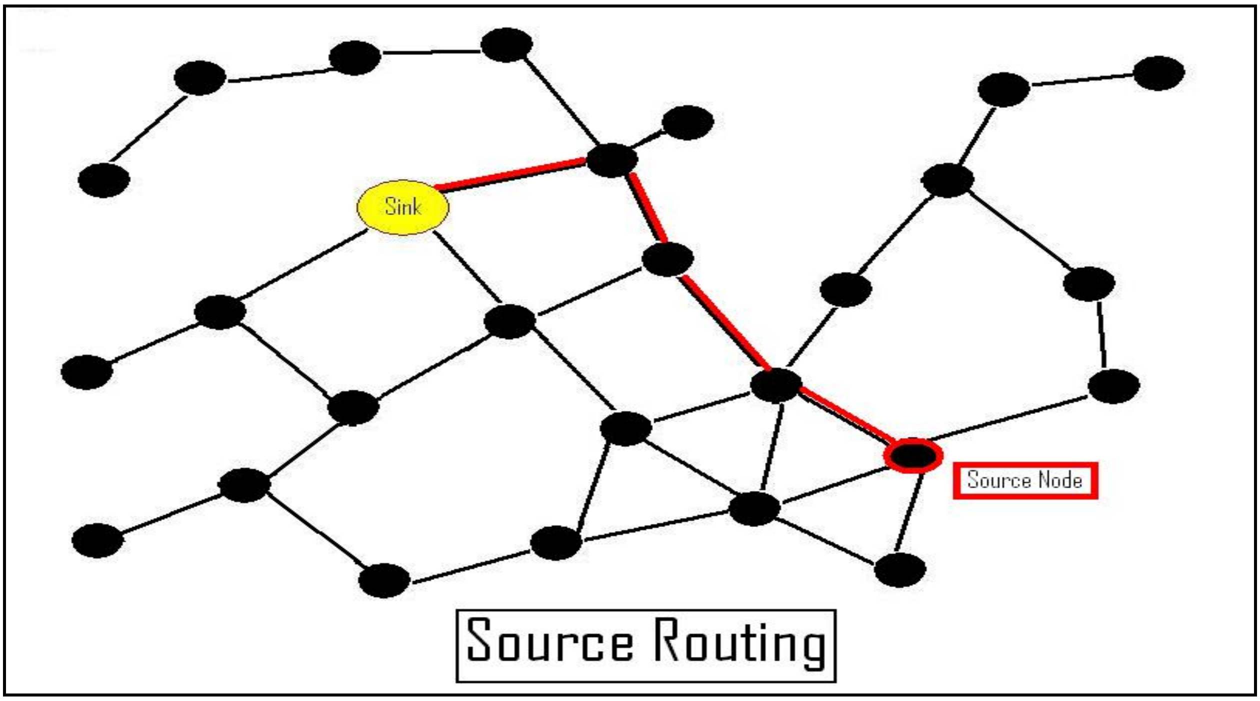


Fig. 5.1: Source Routing Diagram

5.3 Source Routing Algorithm

The source own generated messages:

```
{
Use Source Routing;
Specify the entire path to the sink;
Forward the message to the next node in the path;
}
```

Received messages:

```
{
Use Source Routing;
Forward messages to requested next node (when possible);
}
```

5.4 Diffusion Routing

In Diffusion Routing [LOU05] [ALK04] [MAX75], each node keeps a database of different paths to the sink. For each message to be sent to the sink, the source node will chose only the next node and forward the message to it. The source node will not specify the entire route to the sink. Instead, each node that receives the message will forward it one hop closer to the sink by choosing the next node from one of its known routes. The route selection seeks to smooth out traffic on the WSN, to optimize link capacity and to extend battery life.

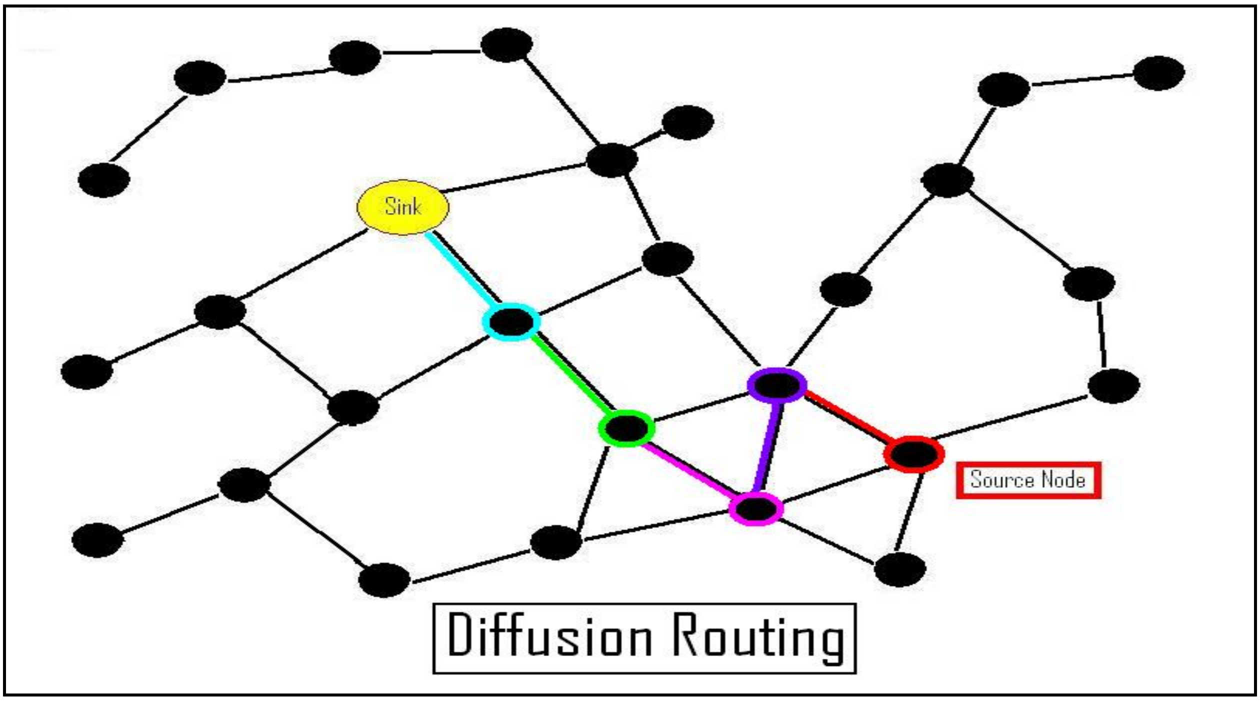


Fig. 5.2: Diffusion Routing Diagram

5.5 Diffusion Routing Algorithm

The source own generated messages:

```
{
Use Diffusion Routing;
Specify only the next hop in the path to the sink,
Forward the message to the next node in the path (when possible);
}
```

Received messages:

```
{
Use Diffusion Routing;
Specify only the next hop in the path to the sink;
Forward the message to the next node in the path (when possible);
}
```

5.6 Hybrid Routing

Each node keeps a database of different paths to the sink. Source Routing will be used when the source node has a large enough number of different routes to make an intelligent route selection. When Source Routing is used, the message follows the exact route specified by the source node. Hence, no Diffusion Routing would be used.

Diffusion Routing will be used when there is not much of a choice for the source node to specify the entire route to the sink. In Diffusion Routing, the source node will only specified the next hop (Receiver Node). When a Receiver Node receives a message without the route to the sink being specified, the Receiver Node will use Source Routing, if there is a large enough number of different routes to the sink to select from. Otherwise, the Receiver Node will use Diffusion Routing again to route the message to the sink.

For any node in the WSN using Hybrid Routing Protocol, the node would switch from the Diffusion Routing to Source Routing when the node discovered a number of routes to the sink bigger than a preset value called cut off value. When a node discovers a number of routes to the sink bigger than or equal to the cut off value then the node would use Source Routing Protocol to forward messages to the sink. On the other hand, if the numbers of routes to the sink discovered by the node were smaller than the cut off value then the node would use the diffusion routing protocol for its message forwarding to the sink.

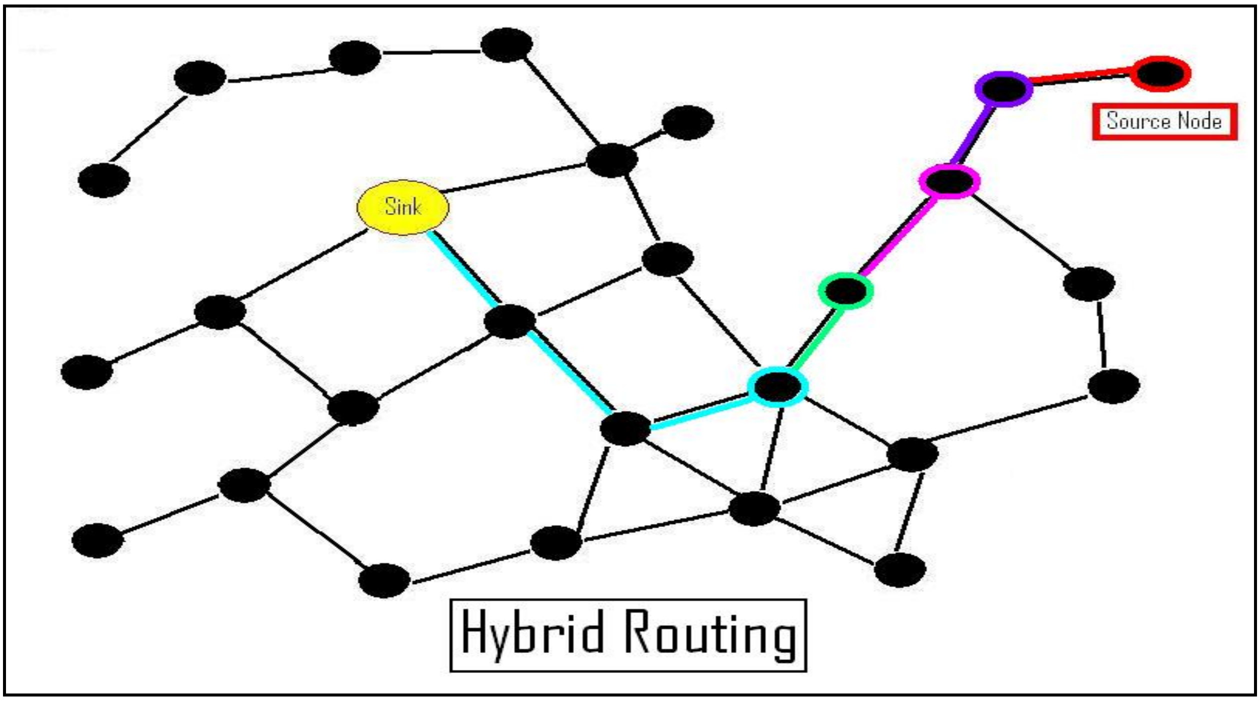


Fig. 5.3: Hybrid Routing Diagram

5.7 Hybrid Routing Algorithm

Switching from Diffusion Routing to Source Routing:

```
If (number of routes discovered by a node >= cut off value){
        Source Routing for the node = true;
}else{
        Diffusion Routing for the node= true;
        }
```

The source own generated messages:

```
If (Source Routing for the node){
        Use Source Routing;
        Specify the entire path to the sink;
        Forward the message to the next node in the path (when possible);
}else{
        Use Diffusion Routing;
        Specify only the next hop in the path to the sink,
        Forward the message to the next node in the path (when possible);
        }
```

Received data packet:

```
If (Diffusion Routing for the message){
        if (Source Routing for the node){
                Use Source Routing;
                Specify the entire path to the sink;
                Forward the message to the next node in the path (when possible);
        }else{
                Use Diffusion Routing;
                Specify only the next hop in the path to the sink;
                Forward the message to the next node in the path (when possible);
                }
}
```

```
If (Source Routing for the message){
        Use Source Routing;
        Forward message to requested next node (when possible);
}
```

The Hybrid Routing Protocol and The Hybrid Routing Protocol Algorithm are both two of the contributions made in this thesis. Also, Source Routing Protocol Algorithm and Diffusion Routing Protocol Algorithm are both two of the contributions made in this thesis.

Chapter 6: Simulations Performance Evaluation

6.1. Introduction

The WSN used for simulation and analyses is the same as the one used by the authors of [GAL07] for their research study. A graphical representation of the WSN used is shown in Fig. 6.1. The simulator program developed used discrete event simulation principals to simulate the network functionality. The programming language used was J2E (Java Enterprise Edition).

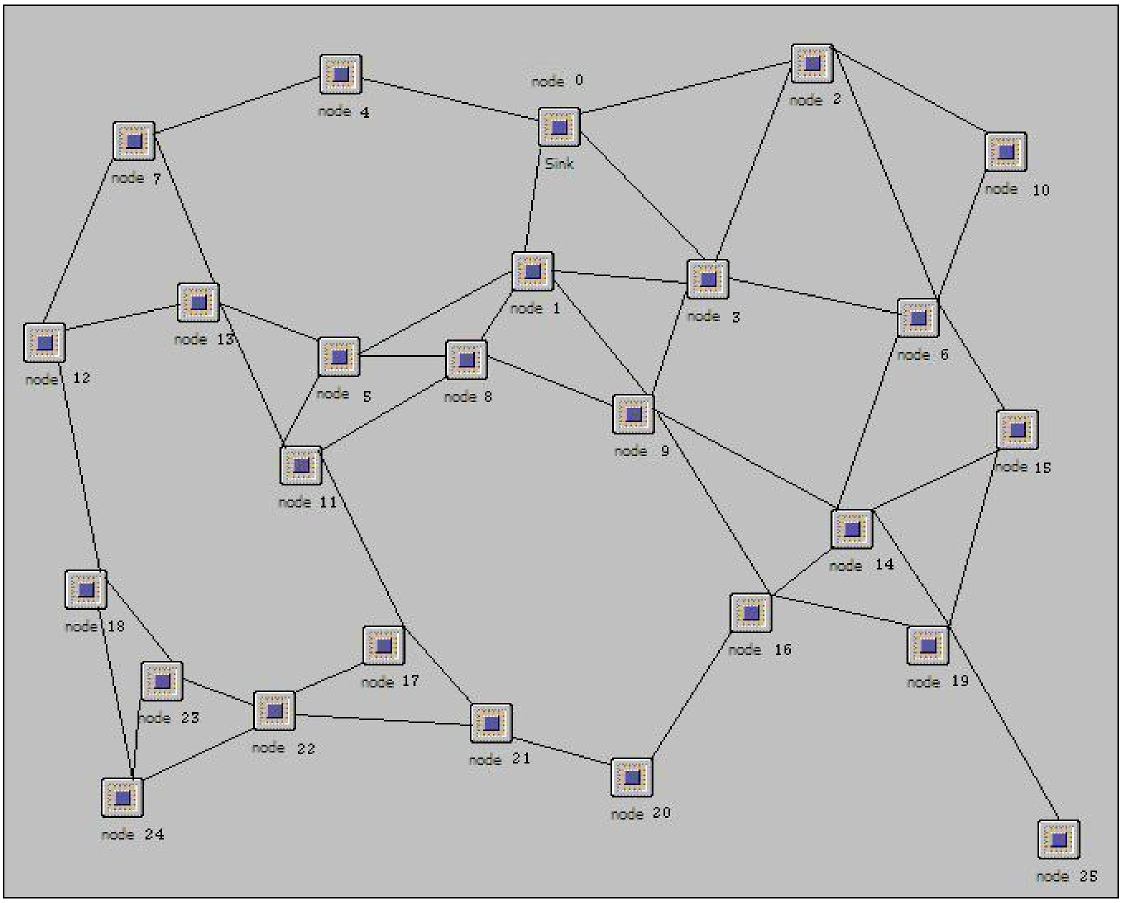


Fig. 6.1: The WSN used for simulation

At the beginning of every simulation run by the program, every node has enough power to send or receive 1000 messages. Also, a unit of time equivalent to the time needed to send or receive one message was used.

6.2 Multipath Finding Protocol

As it is indicated earlier in chapter 2, the original Multipath Finding Protocol [LOU05] is to be carried on in cycles. Each cycle would have the first and the second phase. One could understand the reason behind that is the original protocol was meant for Mobile Ad-hoc and Sensor Systems. Such networks have a changing topology where nodes may go out of power or out of communication range or leave the network due to the mobility of the nodes. Also, new nodes could join the network to extend the network coverage or to replace older nodes or to improve quality of communications. In such changing, mobile and dynamic network the protocol need to be performed in cycles to discover the ever-changing new routes.

On the other hand, none of the factors described above apply to the network used for simulation. For that reason, the Multipath Finding Protocol was carried out once during the simulation process. It was observed that performing the protocols first two phases more than one cycle would only depletes the network power without adding any new routes that was not discovered in the first cycle. This is because; the routes in the network and the connectivity between all nodes would remain the same through the course of the simulation due to the immobility of the nodes.

6.3 Types of Broadcasts

Fig. 6.2 shows the simulation results of using type-two broadcast in phase one of the Multipath Finding Protocol. It is important to point out, the long time it took the network to reach a stat in phase one at simulation time = 9768, where the network is completely non functional because most nodes are out of power. The total number of routes discovered for all nodes using type-two broadcast was in the thousands.

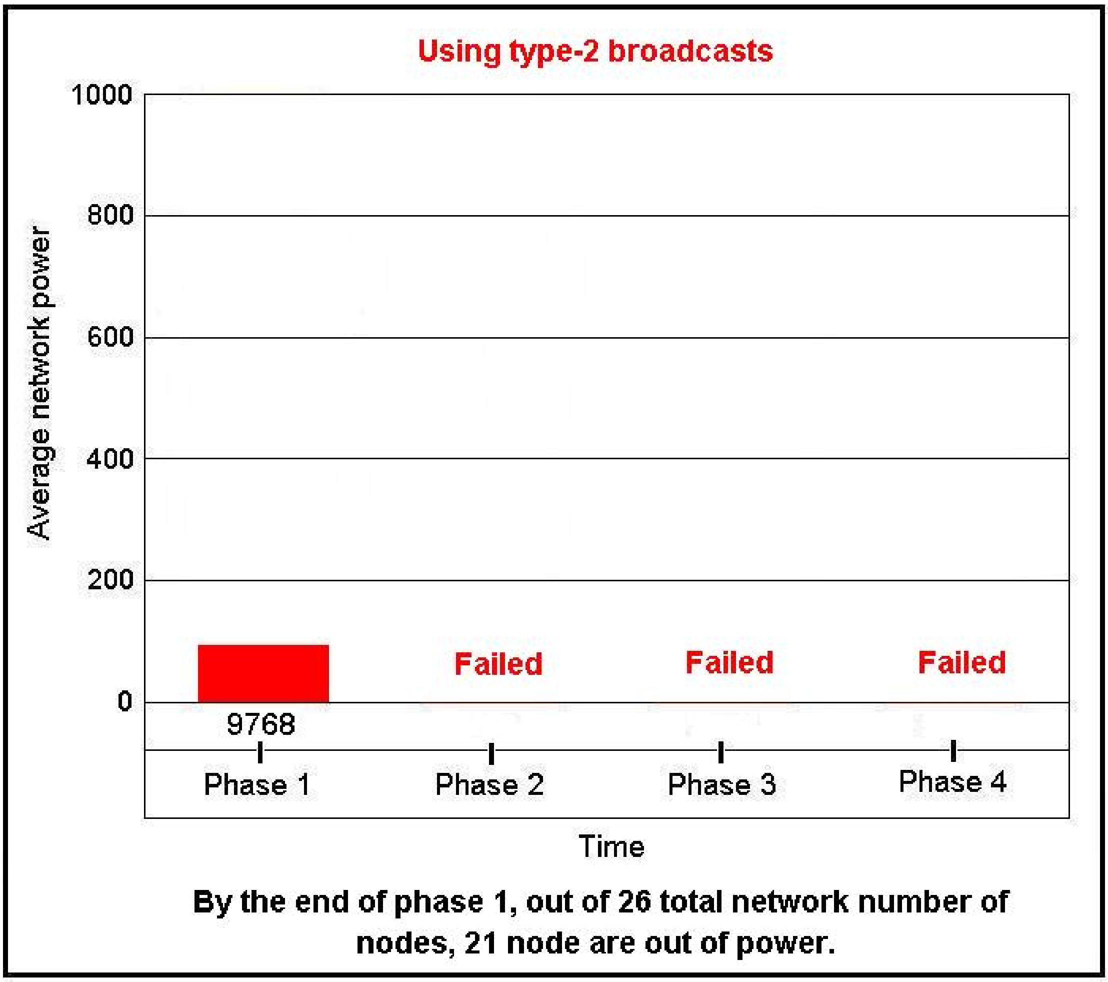


Fig. 6.2: Using type-two broadcast in phase-one of the Multipath finding protocol

Fig. 6.3 shows the simulation results of using type-three broadcast in phase one of the Multipath Finding Protocol. It is important to point out, the time it took type-three broadcast to finish phase one of the multi path finding protocol is much smaller than the time needed by type-two broadcast. Also, a much smaller portion of the network power where used during phase one compared to the power consumed during phase one by type-two broadcast. Even though, 60% of the over all network power are still intact after phase four, the network would be very limited in terms of connectivity and functionality by the end of phase four of the Multipath Finding Protocol. This is because; two of the most used nodes are out of power. The total numbers of routes discovered for all nodes using type-three broadcast were 547 routes.

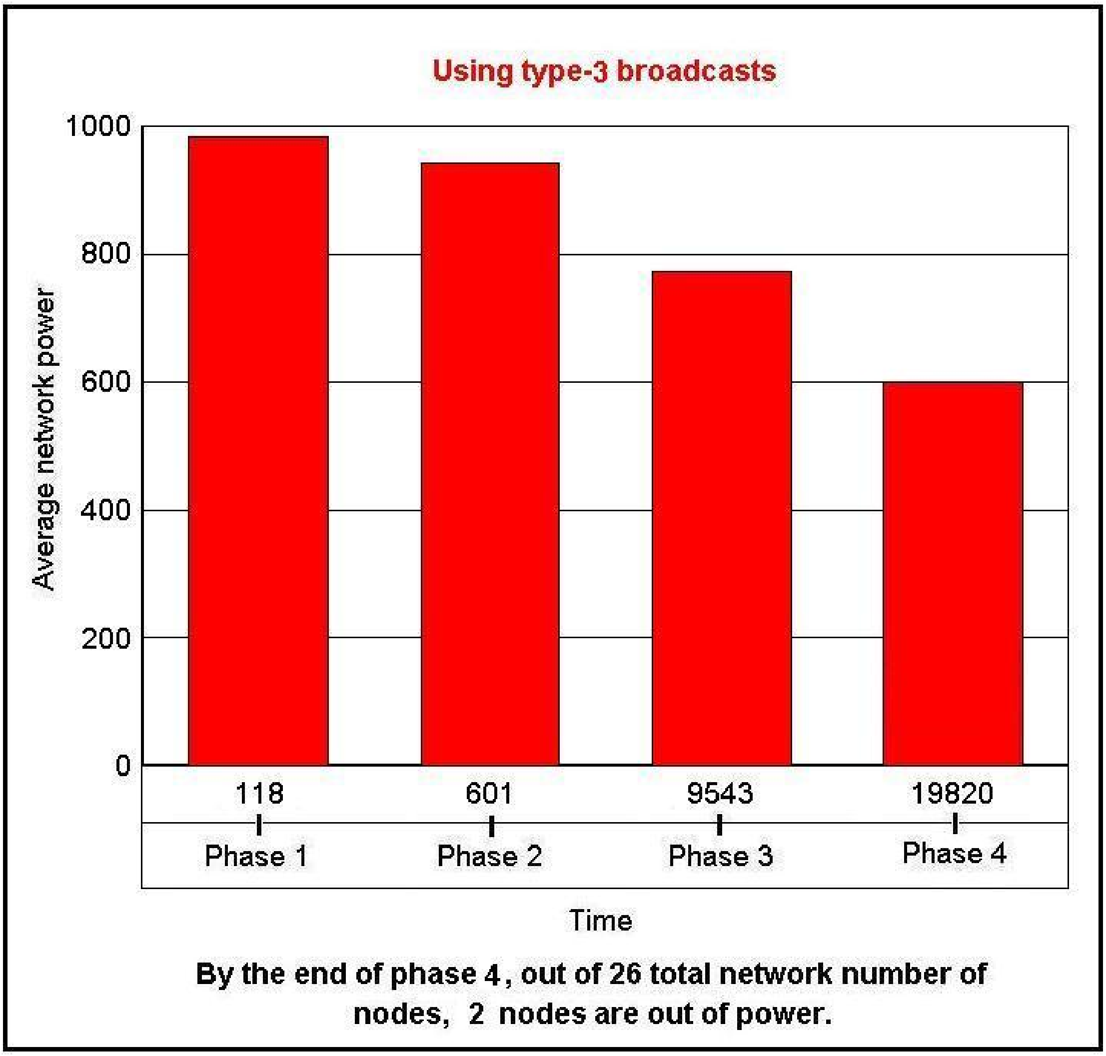


Fig. 6.3: Using type-three broadcast in phase one of the Multipath finding protocol

Fig. 6.4 shows the simulation results of using type-four broadcast in phase one of the Multipath Finding Protocol. It is important to point out; the time it took type-four broadcast to finish phase-one of the Multipath Finding Protocol is much smaller than the time needed by type-three broadcast. Also, a much smaller portion of the network power where used during phase-one compared to the power consumed during phase-one by type-three broadcast. The network would be connected and functional by the end of phase-four of the Multipath Finding Protocol, all nodes would have power to carry on operation mode. Almost 85% of the over all network power are still intact after phase four. The total numbers of routes discovered for all nodes using type-four broadcast are 163 routes.

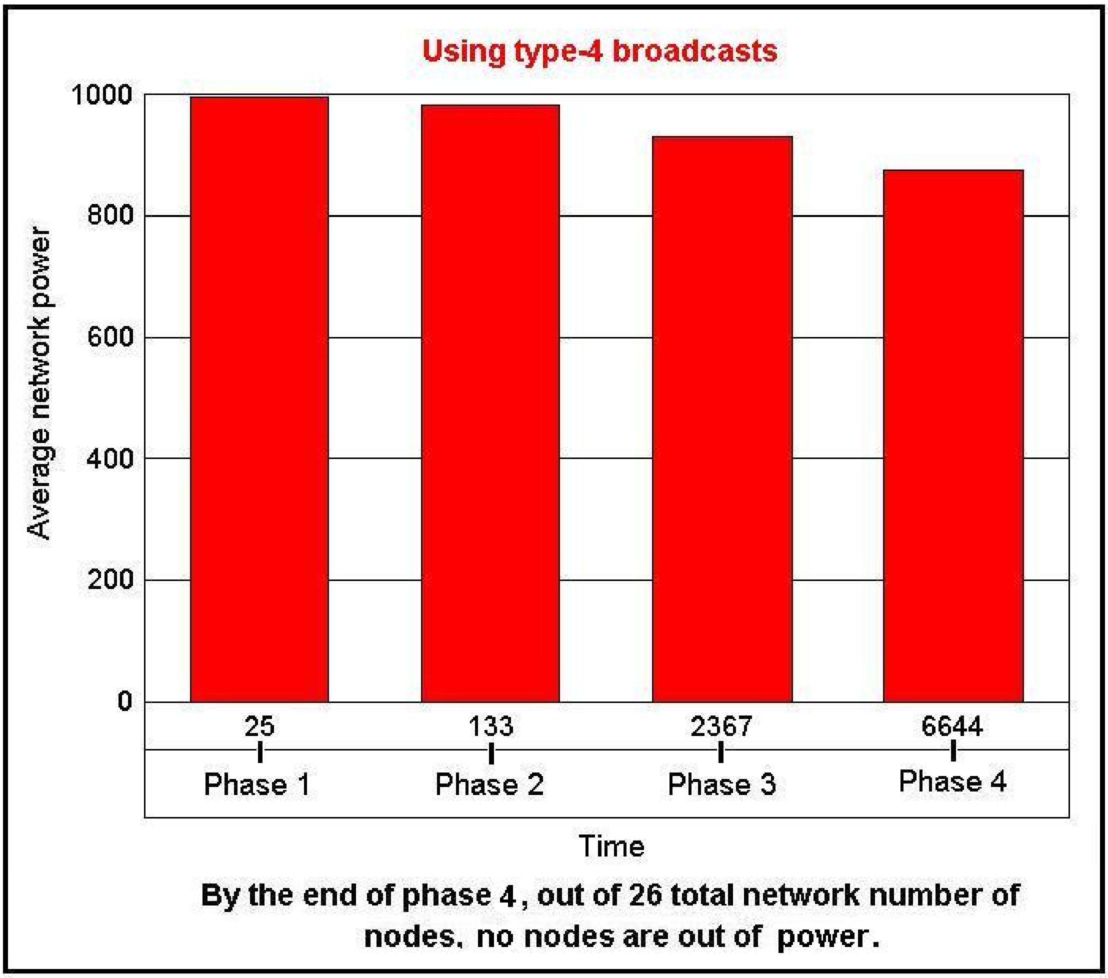


Fig. 6.4: Using type-four broadcast in phase-one of the Multipath finding protocol

6.3.1 Multipath Finding Protocol Efficiency

The maximum optimum number of routes equals the maximum number of Primary Disjoined Routes for all nodes in the network; witch is equal to the number of nodes in Layer-One multiplied by the number of nodes in the network.

The maximum optimum number of routes = 4 * 25 = 100

The Multipath Finding Protocol Efficiency for the network equals the number of Primary Disjoined Routes discovered by all nodes divided by the maximum optimum number of routes for the network multiplied by 100.

Using Type-Three Broadcast in Phase-One of the Multipath Finding Protocol would produce a Multipath Finding Protocol Efficiency that can be calculated as follows:
The Multipath Finding Protocol Efficiency = (60 / 100) * 100 = 60%

Using Type-Four Broadcast in Phase-One of the Multipath Finding Protocol would produce a Multipath Finding Protocol Efficiency that can be calculated as follows:
The Multipath Finding Protocol Efficiency = (60 / 100) * 100 = 60%

6.3.2 Network Routing Efficiency

The Network Routing Efficiency equals the total number of Primary Disjoined Routes discovered by all nodes divided by the total number of routes in use by all nodes multiplied by 100.

Using Type-Three Broadcast in Phase-One of the Multipath Finding Protocol would produce a Network Routing Efficiency that can be calculated as follows:

The Network Routing Efficiency = (60 / 547) * 100 = 11%

Using Type-Four Broadcast in Phase-One of the Multipath Finding Protocol would produce a Network Routing Efficiency that can be calculated as follows:

The Network Routing Efficiency = (60 / 163) * 100 = 37%

6.4 Wireless Sensor Network Layers

Based on results obtained from the network simulator, the WSN could be divided into layers based on the shortest distance from each node to the sink as shown in Fig. 6.5 and Fig. 6.6.

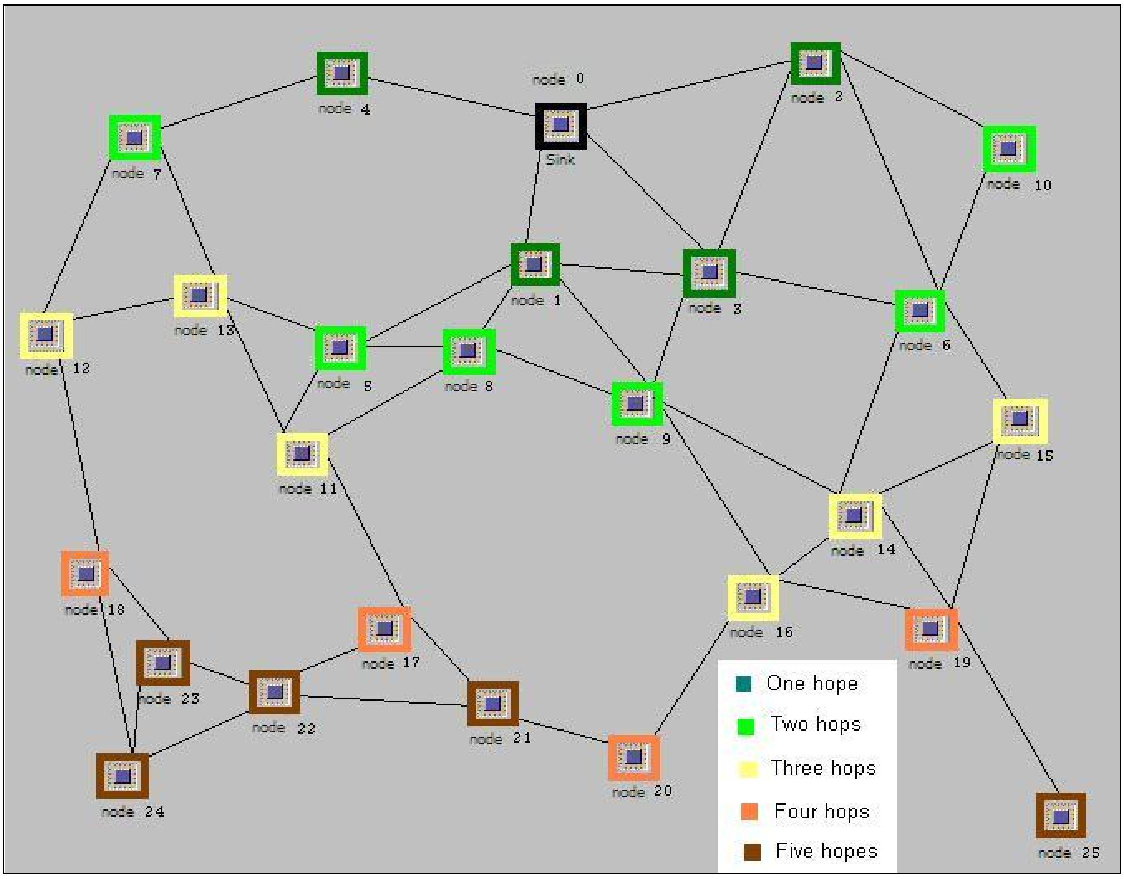
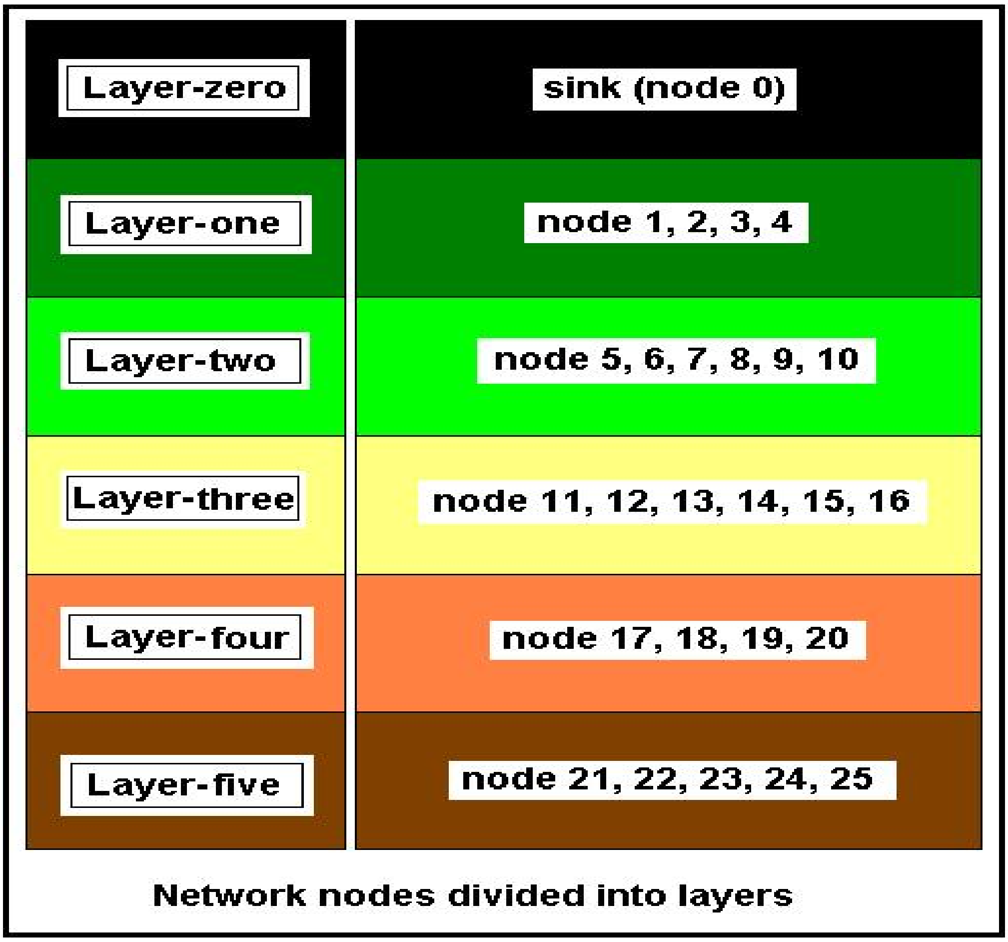


Fig. 6.5: The WSN divided into layers.

The nodes in each layer would only connect to other nodes in the same layer or other nodes in a layer that is one order higher or the nodes in a layer that is one order lower.



Layer-zero	sink (node 0)
Layer-one	node 1, 2, 3, 4
Layer-two	node 5, 6, 7, 8, 9, 10
Layer-three	node 11, 12, 13, 14, 15, 16
Layer-four	node 17, 18, 19, 20
Layer-five	node 21, 22, 23, 24, 25

Network nodes divided into layers

Fig. 6.6: The WSN divided into layers, as all nodes in each layer would have the same distance to the sink

6.5 Types of Paths

In Fig. 6.7, node 7 has two Disjoined Routes to the sink. Fig. 6.8 shows two Disjoined Routes from node 25 to the sink through node 1 and node 2. Even though both routes share the same link between node 25 and node 19, they both are disjoined routes because, the link they share is between two of the lowest network layers and they use different Layer-One nodes.

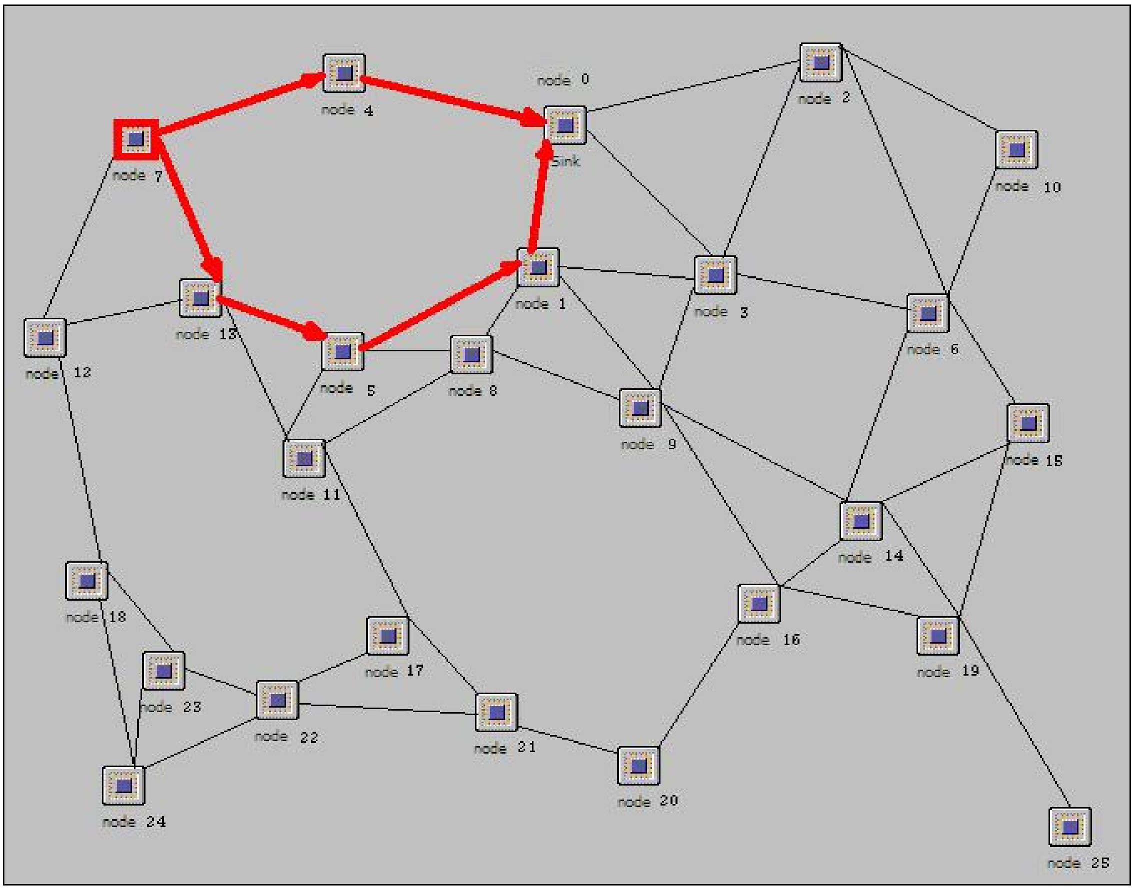


Fig. 6.7: Node 7 has two disjoined paths to the sink

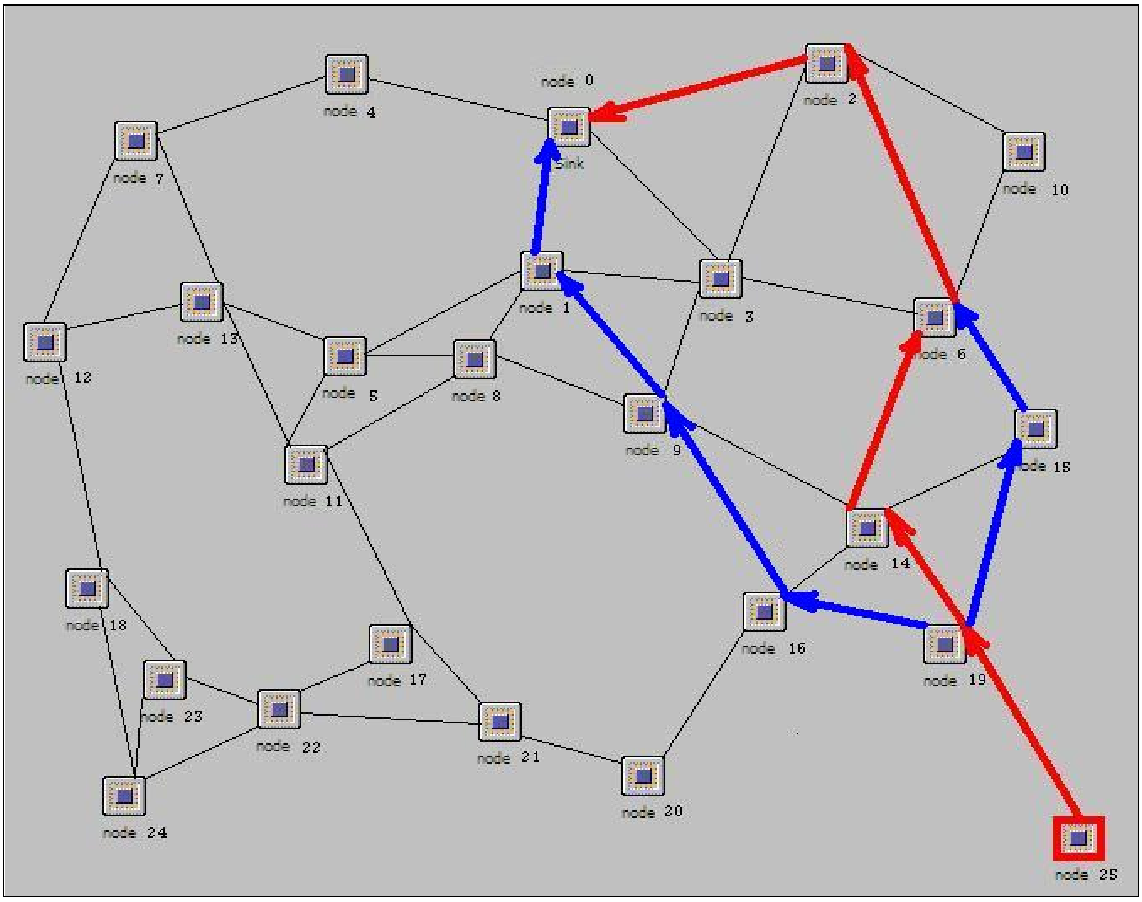


Fig. 6.8: Two disjoined paths and one parallel path from node 25 to sink

In Fig. 6.9, the two paths from node 20 to the sink are joined routes, since both routes use the same Layer-One node, node 1. Attached paths are duplicates paths. In a perfect world, the attached path with the larger number of hops is to be deleted.

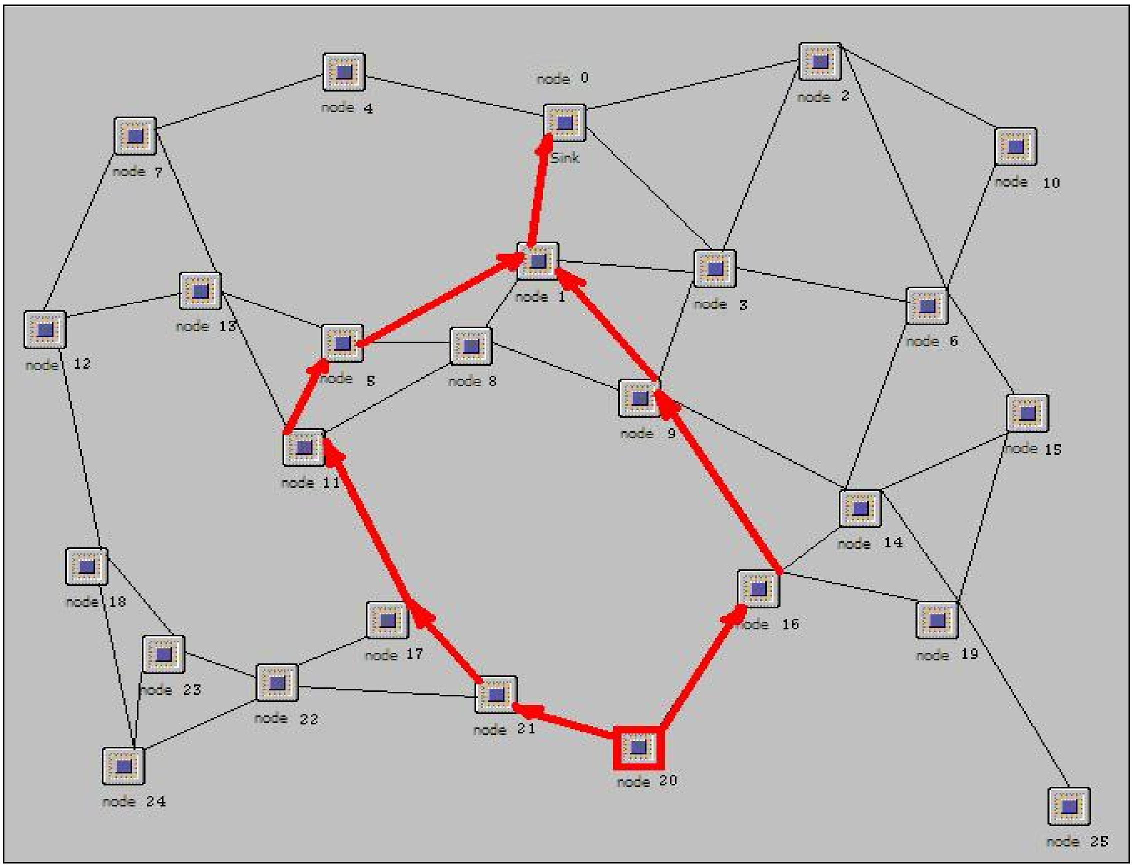


Fig. 6.9: Two joined paths from node 20 to the sink

Fig. 6.10 shows two parallel paths between source node, node 5, and destination node, sink.

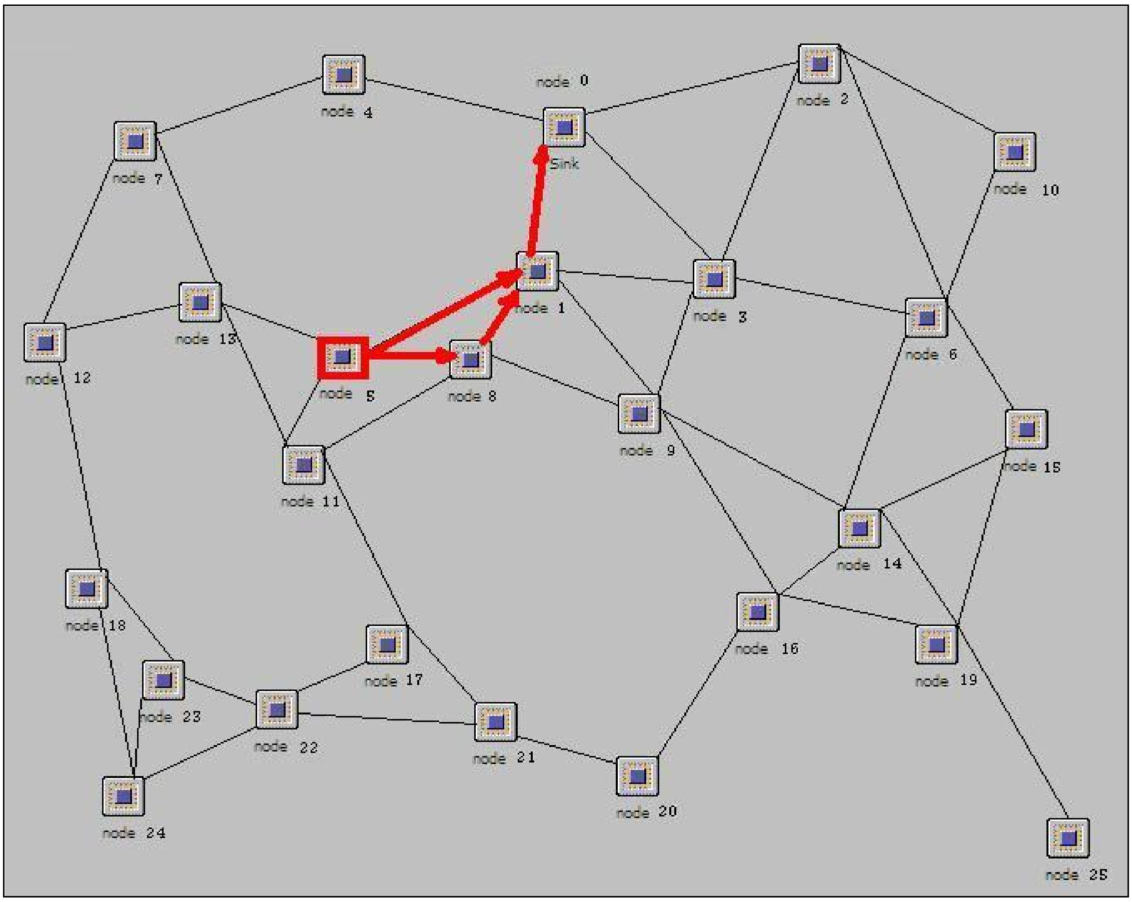


Fig. 6.10: Two parallel paths

The multipath finding protocol as it introduced in [LOU05] and in [GAL07] produced a large number of joined paths, parallel paths, circular paths and long paths. Yet, the joined paths, parallel paths, circular paths and long paths discovered were deleted in those studies. A mechanism to process the routes discovered and delete unwanted paths was in place. The joined route with the smaller number of hops would be kept and the other joined route with the bigger number of hopes would be deleted. Yet, their definition of joined routes is different from the definition provided in this thesis. In [GAL07], two routes from the same source node to the same destination node are joined if they share any similar paths between the two nodes on both paths.

For the purpose of this thesis, no mechanism to delete any discovered routes was used. Thus, all routes discovered were used and none were deleted. The reason for that is to compare the quality of the routes found when changes were to be made to the Multipath Finding Protocol.

For the network that was used for simulation, the longest path ever to be discovered by any node was 7 hops away from the sink. The maximum number of hops for a route for the same network is 9, calculated as follows:
Max. No. Of hops for a path = (2 * 5) – 1 = 9 hops.

6.6 Traffic Splitting Protocol

The network parameters for the simulated network would be calculated as follows:

Network Size Factor:

$$\text{Network Size Factor} = s_f = \frac{(1 * 4) + (2 * 6) + (3 * 6) + (4 * 4) + (5 * 5)}{25} = \frac{75}{25}$$

$$s_f = 3 \text{ hops to sink per node}$$

Network Routing Factor:

$$\text{Network Routing Factor} = r_f = \frac{163}{25} = 6.52 \text{ routes to sink per node}$$

Network Connectivity Factor:

$$\text{Network Connectivity Factor} = c_f = \frac{88}{25} = 3.52 \text{ nodes connected to per node}$$

Network Hops Factor:

$$ß = \frac{1}{3}\left[\frac{3}{(3+1)} + \frac{6.52}{(6.52+1)} + \frac{3.52}{(3.52+1)}\right] = 0.8$$

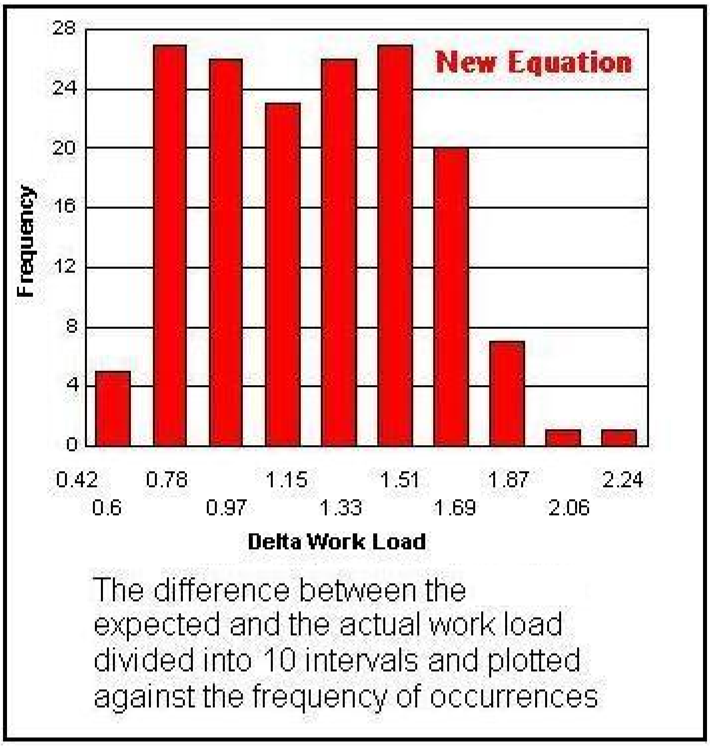
Eq. 4.14 is going to be referred to as the old equation and Eq. 4.10 is going to be referred to as the new equation for the rest of this document.

The difference between the Expected and Actual workload (ΔW_j (k_i) Delta workload) for every route is calculated at the end of simulation. Also, the Normalized Residual Workload for each route is collected. The simulation involved sending 100 messages by each node to the sink. The Delta Workload and the Normalized Residual Workload for every route is plotted against the frequency of occurrences in two cases. In the first case the new equation to calculate the Normalized Residual Workload was used for each route. In the second case, the old equation to calculate the Normalized Residual Workload was used for each route. In both cases, the Normalized Residual Workload for each route would be used by the node to select the most appropriate route for the next message forwarding.

Fig. 6.11 shows the Delta Workload results obtained from computer simulation for the first case. Fig. 6.12 shows the Delta Workload results obtained from computer simulation for the second case. Fig. 6.13 shows a comparison between the Delta Workload results obtained from both cases in one graph.

Fig. 6.14 shows the Normalized Residual Workload results obtained from computer simulation for the first case. Fig. 6.15 shows the Normalized Residual Workload results obtained from a computer simulation for the second case. Fig. 6.16 shows a comparison between the Normalized Residual Workload results obtained from both cases in one graph.

A summery of the measured differences in performance between the results obtained from using the new equation and the old equation are shown in able 6.1, table 6.2, table 6.3 and table 6.4.



The difference between the expected and the actual work load divided into 10 intervals and plotted against the frequency of occurrences

Fig. 6.11: Delta Workload using New Equation

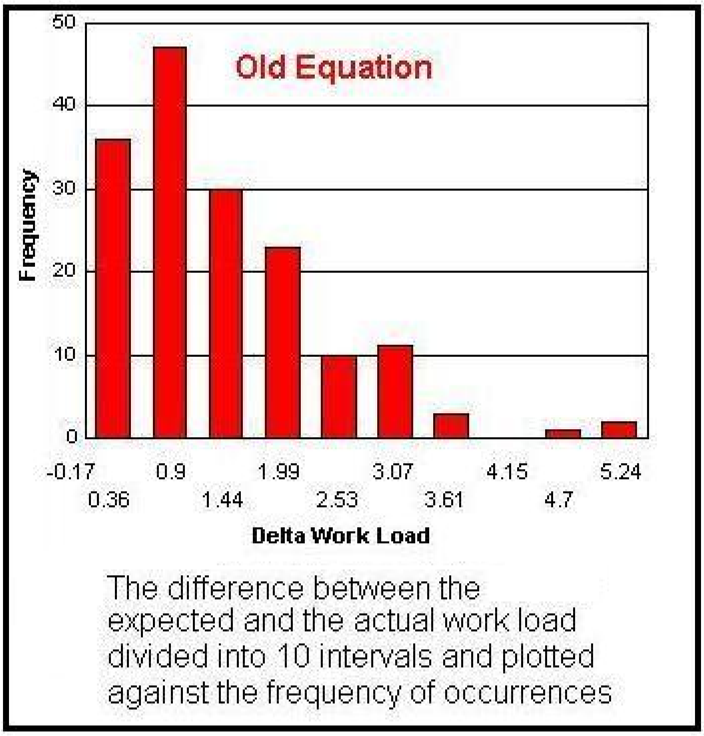


Fig. 6.12: Delta Workload using Old Equation

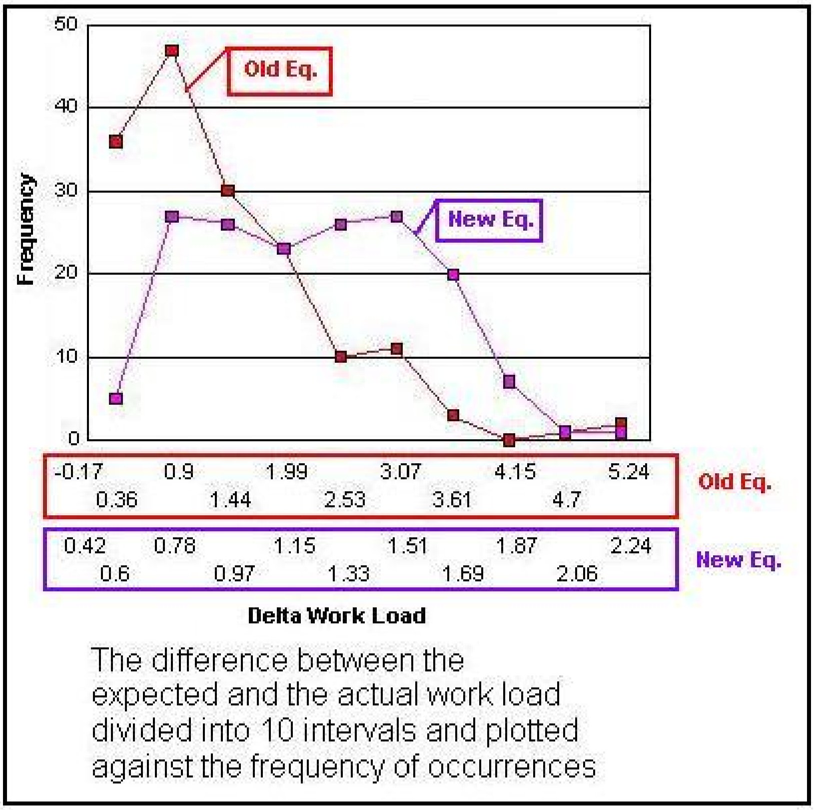
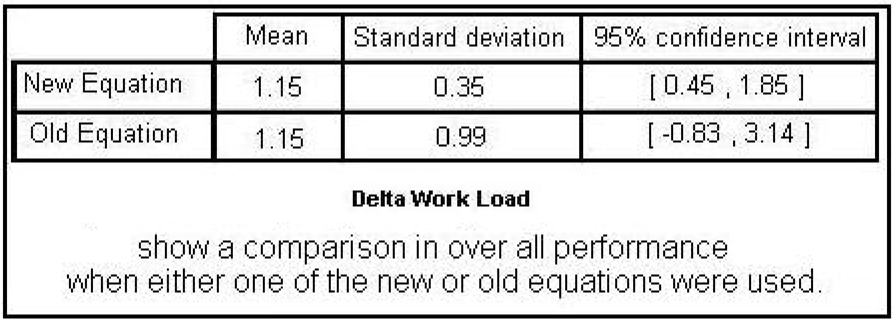


Fig. 6.13: Delta Workload of both New and Old Equation

Comparisons between the Delta Workload results obtained from simulation from both cases are shown in Table 6.1 and Table 6.2. The values of the Mean, Standard deviation and the 95% confidence interval for Delta workload when the new equation is used and when the old equation is used are shown in Table 6.1.

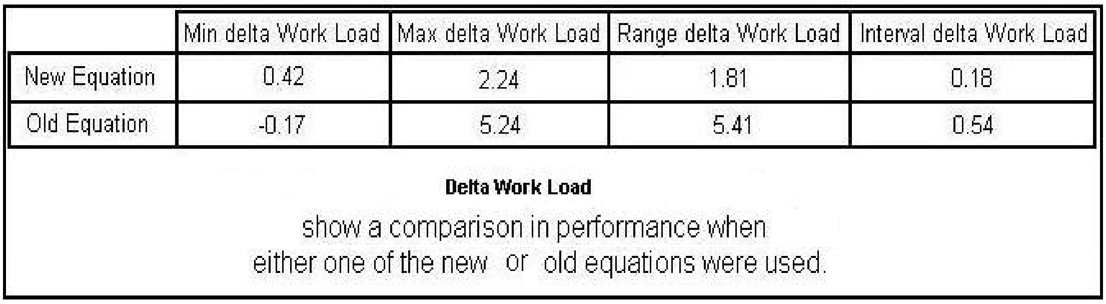


	Mean	Standard deviation	95% confidence interval
New Equation	1.15	0.35	[0.45 , 1.85]
Old Equation	1.15	0.99	[-0.83 , 3.14]

Delta Work Load

show a comparison in over all performance
when either one of the new or old equations were used.

Table 6.1: Delta Workload of both New and Old Equation



	Min delta Work Load	Max delta Work Load	Range delta Work Load	Interval delta Work Load
New Equation	0.42	2.24	1.81	0.18
Old Equation	-0.17	5.24	5.41	0.54

Delta Work Load

show a comparison in performance when
either one of the new or old equations were used.

Table 6.2: Delta Workload of both New and Old Equation

Table 6.1 shows, when either of the old or new equation is used during the simulations, both would result in an under use of 1.15 message per route as a universal mean across the network. Even though, the new equation distributes network traffics more evenly and efficiently across different paths than the old equation. The improvement in performance is not reflected in the value of the Delta workload statistical mean. This is because; the numbers of messages routed by all nodes are the same in both cases (100 messages per node).

Table 6.1 shows, the new equation would results in an under use of 0.45 messages or 1.85 message or any thing in between 95% of the time on all routes in the WSN. On the other hand, the old equation would results in either an over use of 0.83 messages or under used of 3.14 messages or any thing in between 95% of the time on all routes in the WSN.

Table 6.1 shows a big difference in the standard deviation of Delta Workload when either the new or old equation is used. The stander deviation of Delta Workload when the new equation is used is 1/3 the value of the stander deviation of Delta Workload when the old equation is used. This resulted in a 95% confidence interval for Delta Workload that is 3 times smaller, when the new equation is used compared to when the old equation is used. This means, the capacity of each route is more efficiently used when the new equation is used compared to the old equation. Also, the 95% confidence interval for Delta Workload when the new equation is used is closer to the zero than the 95% confidence interval when the old equation is used. The 100% efficacy in route allocation and usage is at zero.

Table 6.2 shows, using the new equation would result in a scenario where the most used route is under used by 0.42 messages and the least used route is under used by 2.24 messages. On the other hand, using the old equation would result in a scenario where the most used route is over used by 0.17 messages and the least used route is under used by 5.24 messages.

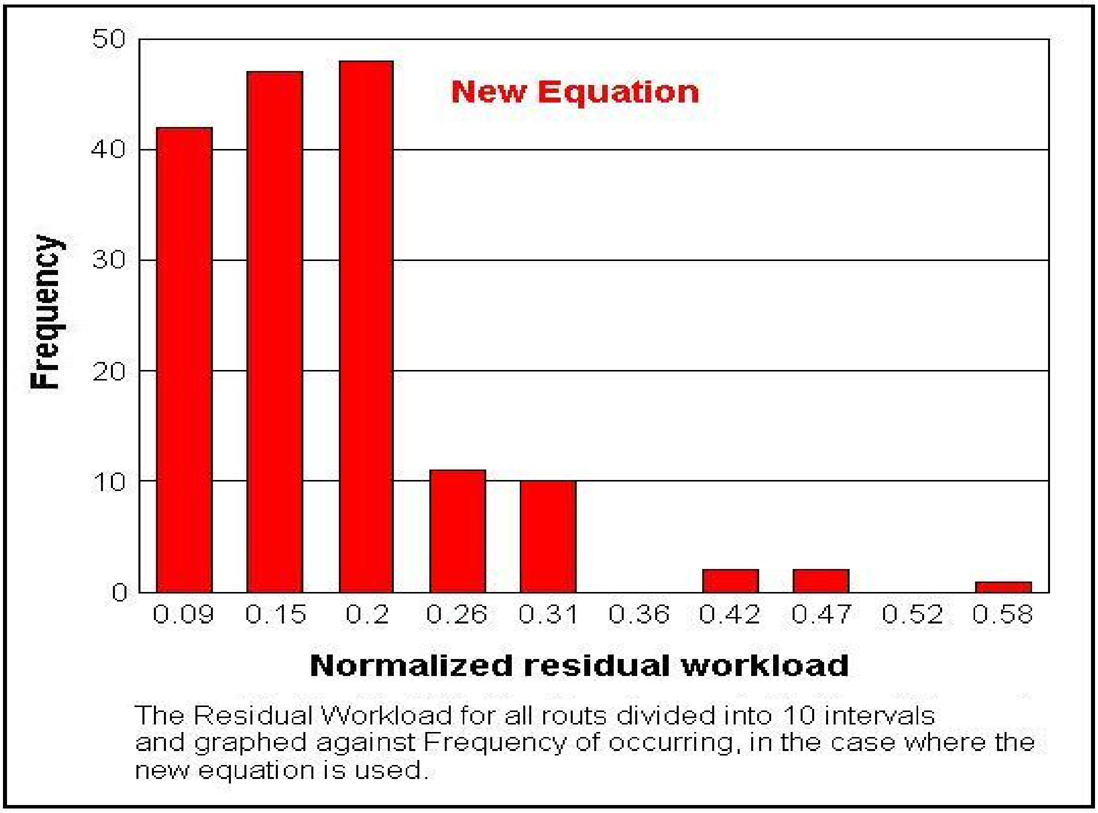


Fig. 6.14: Normalized Residual Workload using New Equation

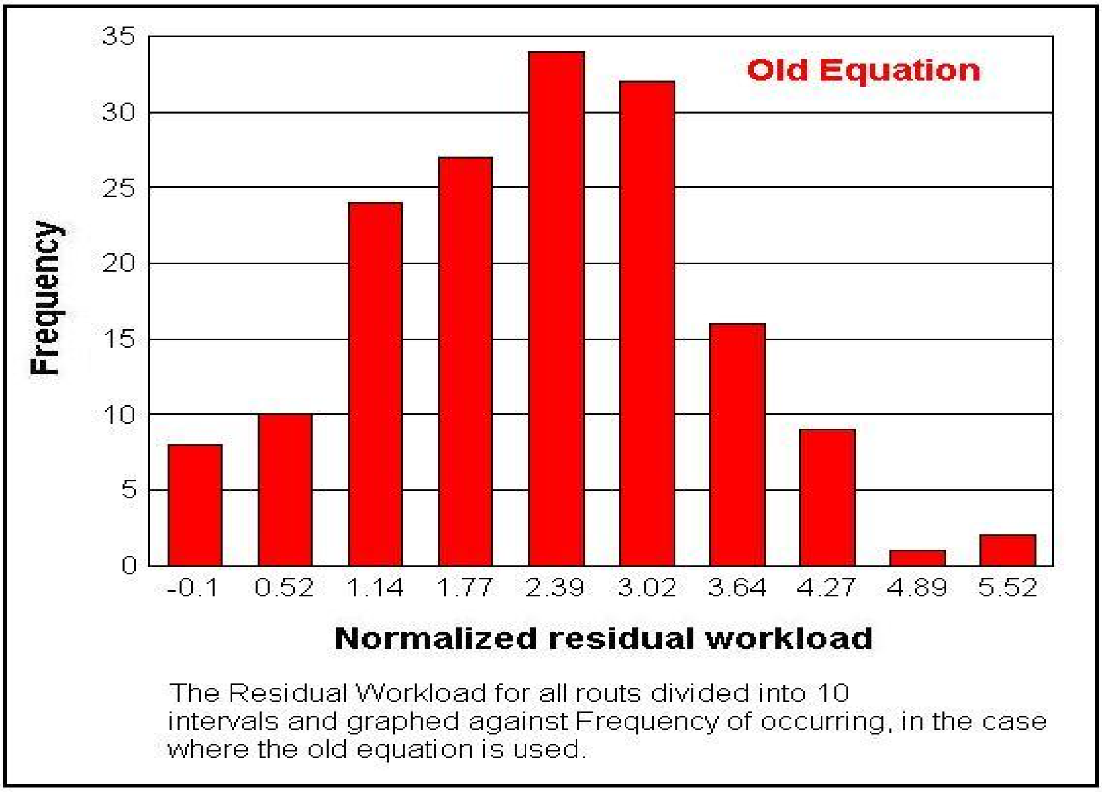
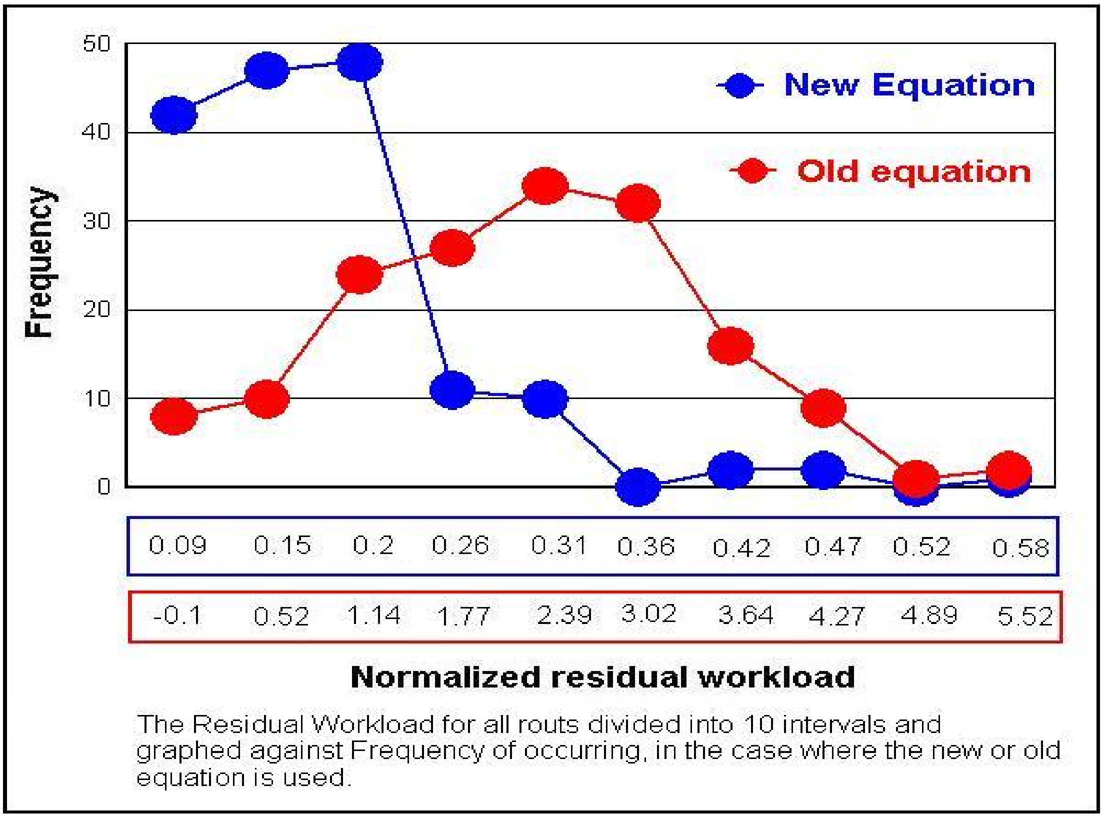


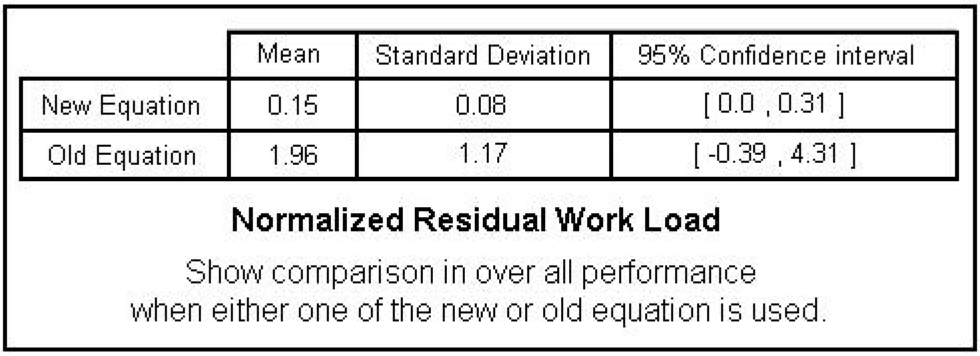
Fig. 6.15: Normalized Residual Workload using Old Equation



The Residual Workload for all routs divided into 10 intervals and graphed against Frequency of occurring, in the case where the new or old equation is used.

Fig. 6.16: Normalized Residual Workload of both New and Old Equation

Comparisons between the Normalized Residual Workload results obtained from simulation from both cases are shown in Table 6.3 and Table 6.4. The values of the Mean, Standard deviation and the 95% confidence interval when the new equation is used and when the old equation is used are shown in Table 6.3.

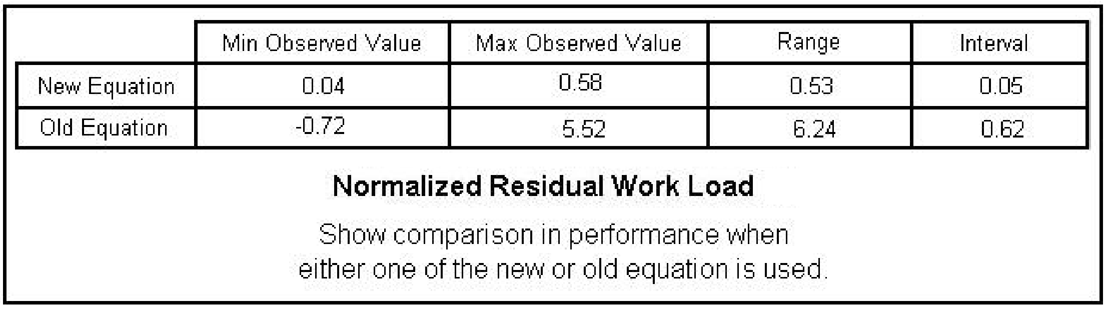


	Mean	Standard Deviation	95% Confidence interval
New Equation	0.15	0.08	[0.0 , 0.31]
Old Equation	1.96	1.17	[-0.39 , 4.31]

Normalized Residual Work Load

Show comparison in over all performance
when either one of the new or old equation is used.

Table 6.3: Normalized Residual Workload of both New and Old Equation



	Min Observed Value	Max Observed Value	Range	Interval
New Equation	0.04	0.58	0.53	0.05
Old Equation	-0.72	5.52	6.24	0.62

Normalized Residual Work Load

Show comparison in performance when
either one of the new or old equation is used.

Table 6.4: Normalized Residual Workload of both New and Old Equation

Table 6.3 shows, Normalized Residual Workload mean when the new equation is used is much smaller than Normalized Residual Workload mean when the old equation is used. The new equation results in an under use of 0.15 message per route as a universal mean across the network. On the other hand, the old equation results in an under use of 1.96 message per route as a universal mean across the network. The new equation distributes network traffics more evenly and efficiently across different paths than the old equation. The improvement in performance is reflected in the value of the Normalized Residual Workload statistical mean. The new equation helps to keep the Actual Workload closer to the Expected Workload more than the old equation would.

Table 6.3 shows, the new equation would results in an under use of 0 messages or 0.31 messages or any thing in between 95% of the time on all routes in the WSN. On the other hand, using the old equation would results in either an over use of 0.39 messages or under used of 4.31 messages or any thing in between 95% of the time on all routes in the WSN.

Table 6.3 shows a big difference in the standard deviation of Normalized Residual Workload when either the new or old equation is used. The stander deviation of

Normalized Residual Workload when the new equation is used is 7% the value of the stander deviation of Normalized Residual Workload when the old equation is used. This resulted in a 95% confidence interval for Normalized Residual Workload that is 14 times smaller, when the new equation is used compared to when the old equation is used. This means, the capacity of each route is more efficiently used when the new equation is used compared to the old equation. Also, the 95% confidence interval for Normalized Residual Workload when the new equation is used is closer to the zero than the 95% confidence interval when the old equation is used. The 100% efficacy in route allocation and usage is at zero.

Table 6.4 shows, using the new equation would result in a scenario where the most used route is under used by 0.04 messages and the least used route is under used by 0.58 messages. On the other hand, using the old equation would result in a scenario where the most used route is over used by 0.72 messages and the least used route is under used by 5.52 messages.

6.7 Hybrid Routing Protocol

In total there were 12 network simulations. One where the Source Routing Protocol was used to route messages from each node to the sink. Another network simulation used the Diffusion Routing Protocol instead to route messages from each node to the sink. In the remaining 10-network simulation, the Hybrid Routing Protocol was used with different cut off value for each network simulation to route messages from each node to the sink. Also, for each of the 12 network simulations, 200 independent runs were performed.

The MAC protocol used for the physical network layer is IEEE 802.11. In the simulation program, a random node would be selected to generate a message to the sink every a random period of time. Every node queue its messages in order to broadcast them one by one to the next node. Depending on the messages generation rate, the message queues would get longer or shorter as the generation rate get higher or lower. For the network simulation, the message generation rate was the same for all of the 12 network simulations. Also, a value for the network parameter ß = 1 was used.

All routing protocols, the Source Routing Protocol, the Diffusion Routing Protocol and the Hybrid Routing Protocol, use the same Multipath Finding Protocol and have the same routs to the sink. Also, all of the routing protocols use the same Traffic Splitting Protocol.

In the case where the Hybrid Routing Protocol was used, the cut off value indicate the minimum number of routes discovered by a node for the Source Routing Protocol to be used. Otherwise, the Diffusion Routing Protocol would be used.

For each of the network simulation runs, messages generated at different nodes in the network were routed to the sink. There was no message loses. So, all the messages generated made it eventually to the sink. As each individual message reach the sink, the simulation program calculates how long of a delay it took each message to travel from the source node to the sink. The delay is measured in units of time, where one unit of time is the time it took a node to broadcast one message. Also, the simulation program calculates how many hopes were needed for each message to reach the sink.

Fig. 6.17 shows the average delay per node for messages routed to the sink using either the Source Routing Protocol or the Diffusion Routing Protocol or the Hybrid Routing Protocol with different cut off values.

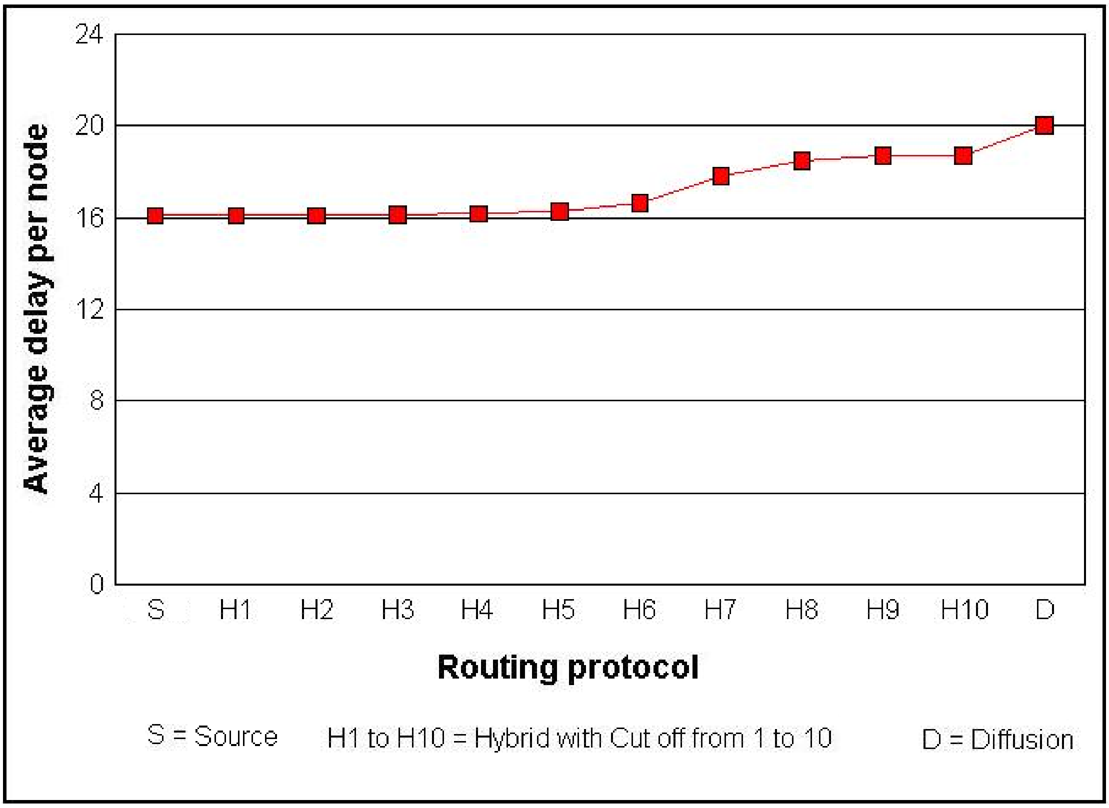


Fig. 6.17: Routing Protocols Average delay

Fig. 6.18 shows the average hops per node needed for messages routed to the sink using either the Source Routing Protocol or the Diffusion Routing Protocol or the Hybrid Routing Protocol with different cut off values.

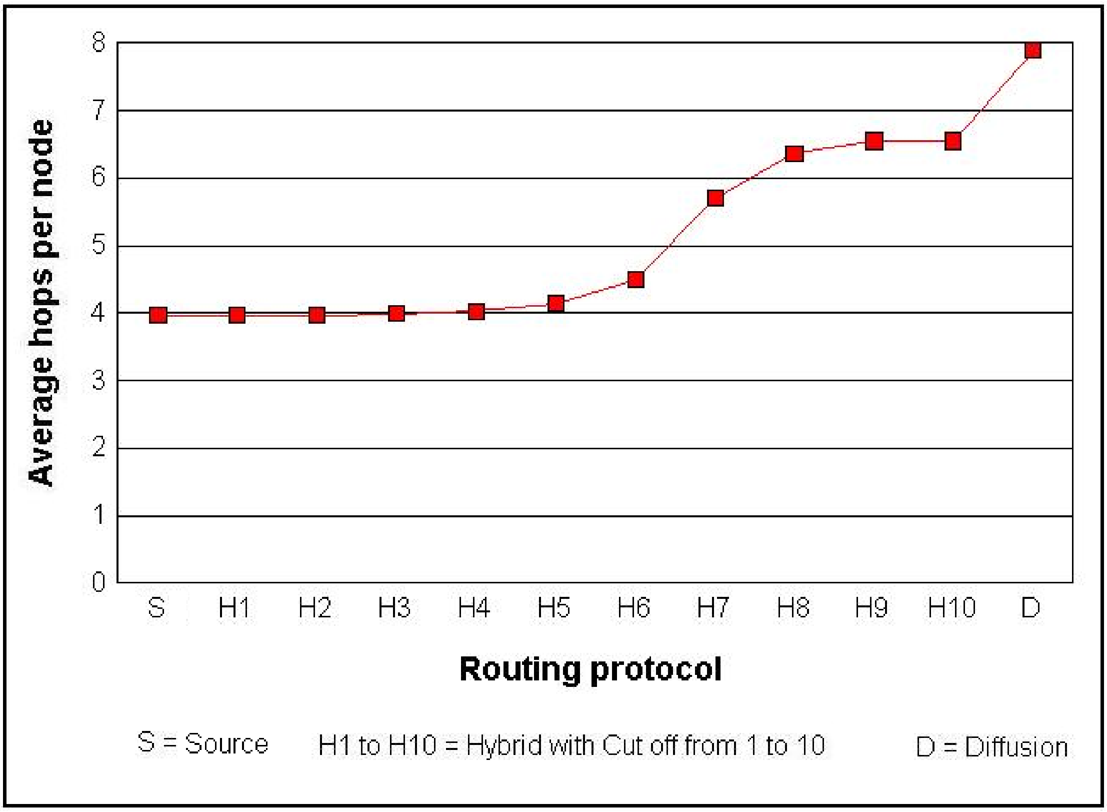


Fig. 6.18: Routing Protocols Average Hops

Fig. 6.19 shows the average residual power per node when either the Source Routing Protocol or the Diffusion Routing Protocol or the Hybrid Routing Protocol with different cut off values is used.

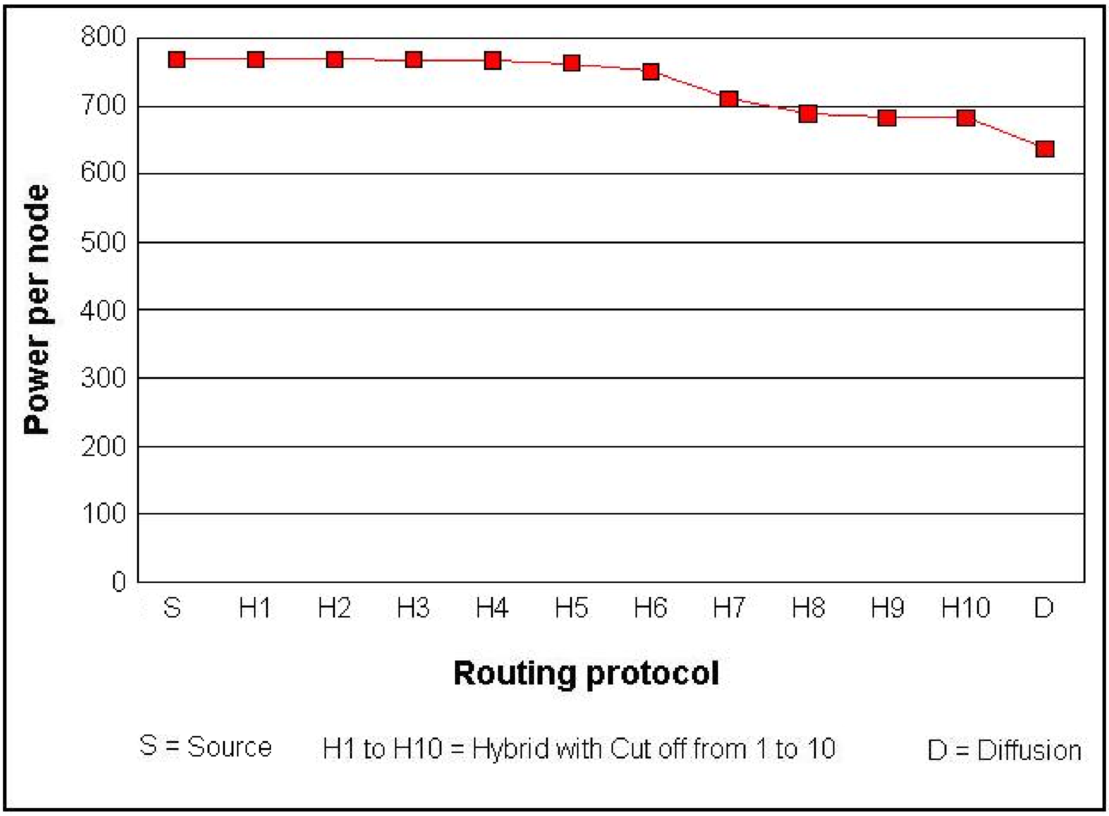
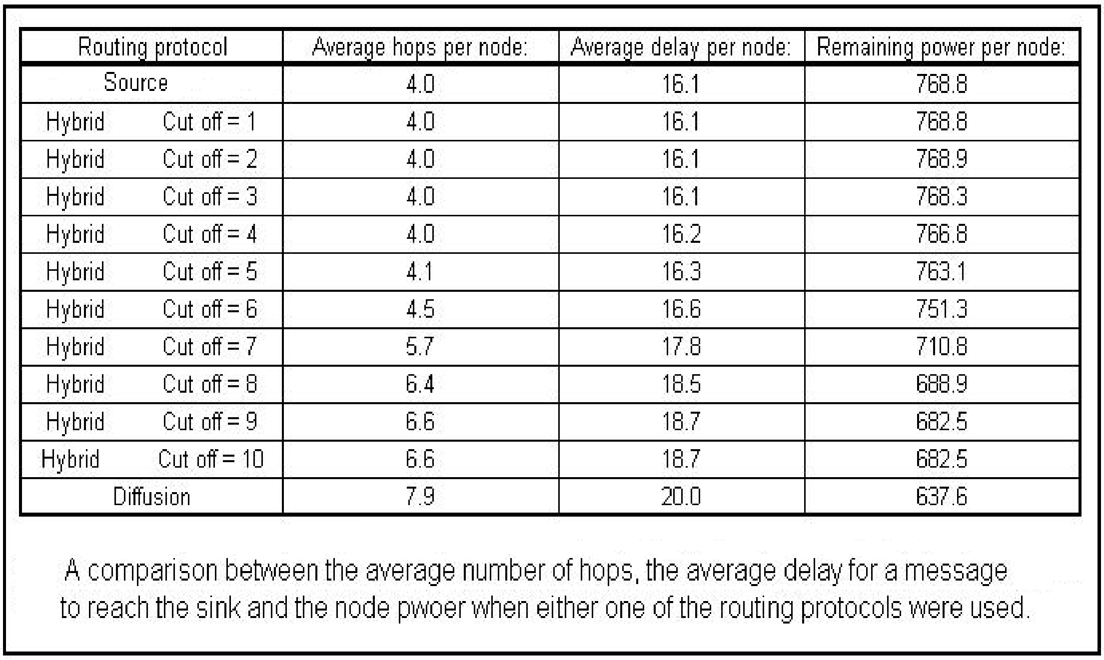


Fig. 6.19: Routing Protocols Power

Table 6.5 shows a comparison between the average number of hops and average delay for a message to reach the sink when either one of the routing protocols were used. Also, the average remaining node power is shown for each routing protocol.

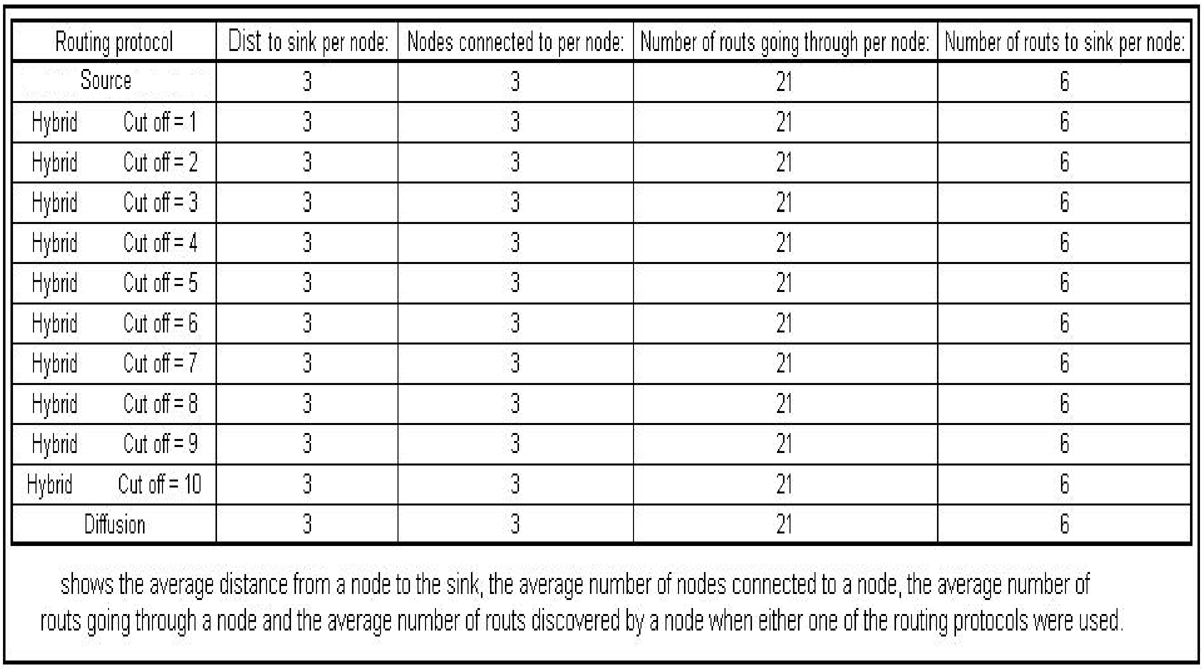


Routing protocol	Average hops per node:	Average delay per node:	Remaining power per node:
Source	4.0	16.1	768.8
Hybrid Cut off = 1	4.0	16.1	768.8
Hybrid Cut off = 2	4.0	16.1	768.9
Hybrid Cut off = 3	4.0	16.1	768.3
Hybrid Cut off = 4	4.0	16.2	766.8
Hybrid Cut off = 5	4.1	16.3	763.1
Hybrid Cut off = 6	4.5	16.6	751.3
Hybrid Cut off = 7	5.7	17.8	710.8
Hybrid Cut off = 8	6.4	18.5	688.9
Hybrid Cut off = 9	6.6	18.7	682.5
Hybrid Cut off = 10	6.6	18.7	682.5
Diffusion	7.9	20.0	637.6

A comparison between the average number of hops, the average delay for a message to reach the sink and the node pwoer when either one of the routing protocols were used.

Table 6.5: Routing Protocols Average delay, Average Hops and Power

Table 6.6 shows a comparison between the average distance from any node in the network to the sink, the average number of nodes connected to any node in the network, the average number of routes going through any node in the network and the average number of routes discovered from any node in the network to the sink when either one of the routing protocols were used.



Routing protocol	Dist to sink per node:	Nodes connected to per node:	Number of routs going through per node:	Number of routs to sink per node:
Source	3	3	21	6
Hybrid Cut off = 1	3	3	21	6
Hybrid Cut off = 2	3	3	21	6
Hybrid Cut off = 3	3	3	21	6
Hybrid Cut off = 4	3	3	21	6
Hybrid Cut off = 5	3	3	21	6
Hybrid Cut off = 6	3	3	21	6
Hybrid Cut off = 7	3	3	21	6
Hybrid Cut off = 8	3	3	21	6
Hybrid Cut off = 9	3	3	21	6
Hybrid Cut off = 10	3	3	21	6
Diffusion	3	3	21	6

shows the average distance from a node to the sink, the average number of nodes connected to a node, the average number of routs going through a node and the average number of routs discovered by a node when either one of the routing protocols were used.

Table 6.6: Routing Protocols Factors

At the end of each run, relative to the total messages received by the sink, the simulator calculates the percentage of messages where the delay was longer than 20 unit of time and the percentage of messages were the number of hops it took the message to reach the sink is greater than 3. After 200 simulation runs were performed for each of the 12-network, statistical analyses were performed on the data collected on both the delays and the number of hops experienced by each of the messages to the sink, Fig. 6.20, Fig. 6.21, Fig. 6.22, Fig. 6.23, Table 6.7 and Table 6.8.

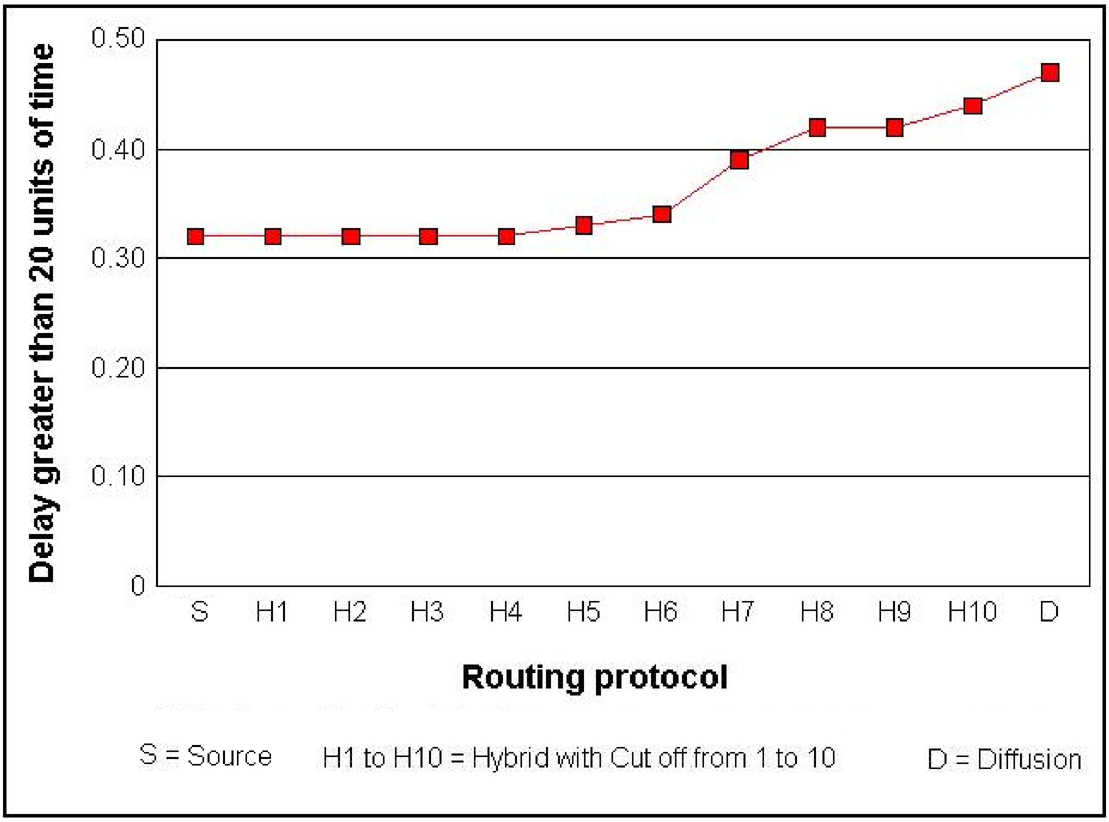


Fig. 6.20: Routing Protocols Delay greater than 20

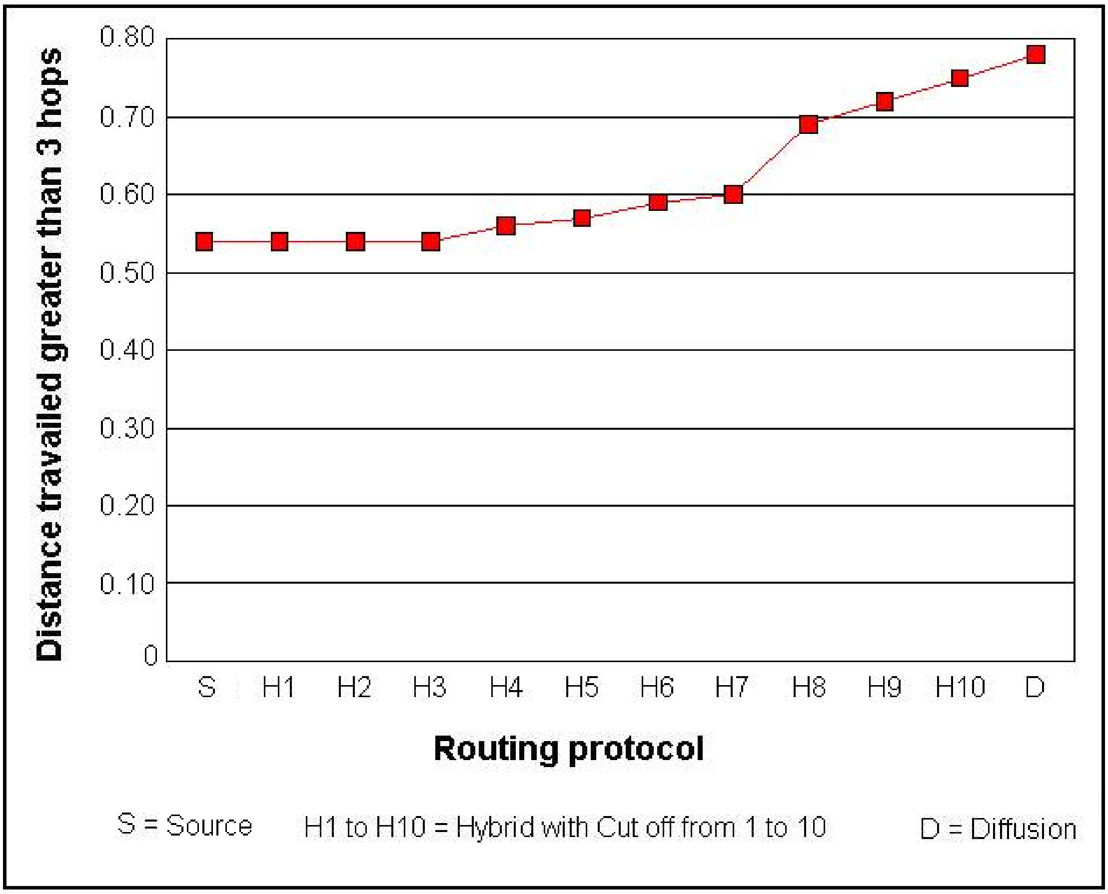


Fig. 6.21: Routing Protocols Distance greater than 3

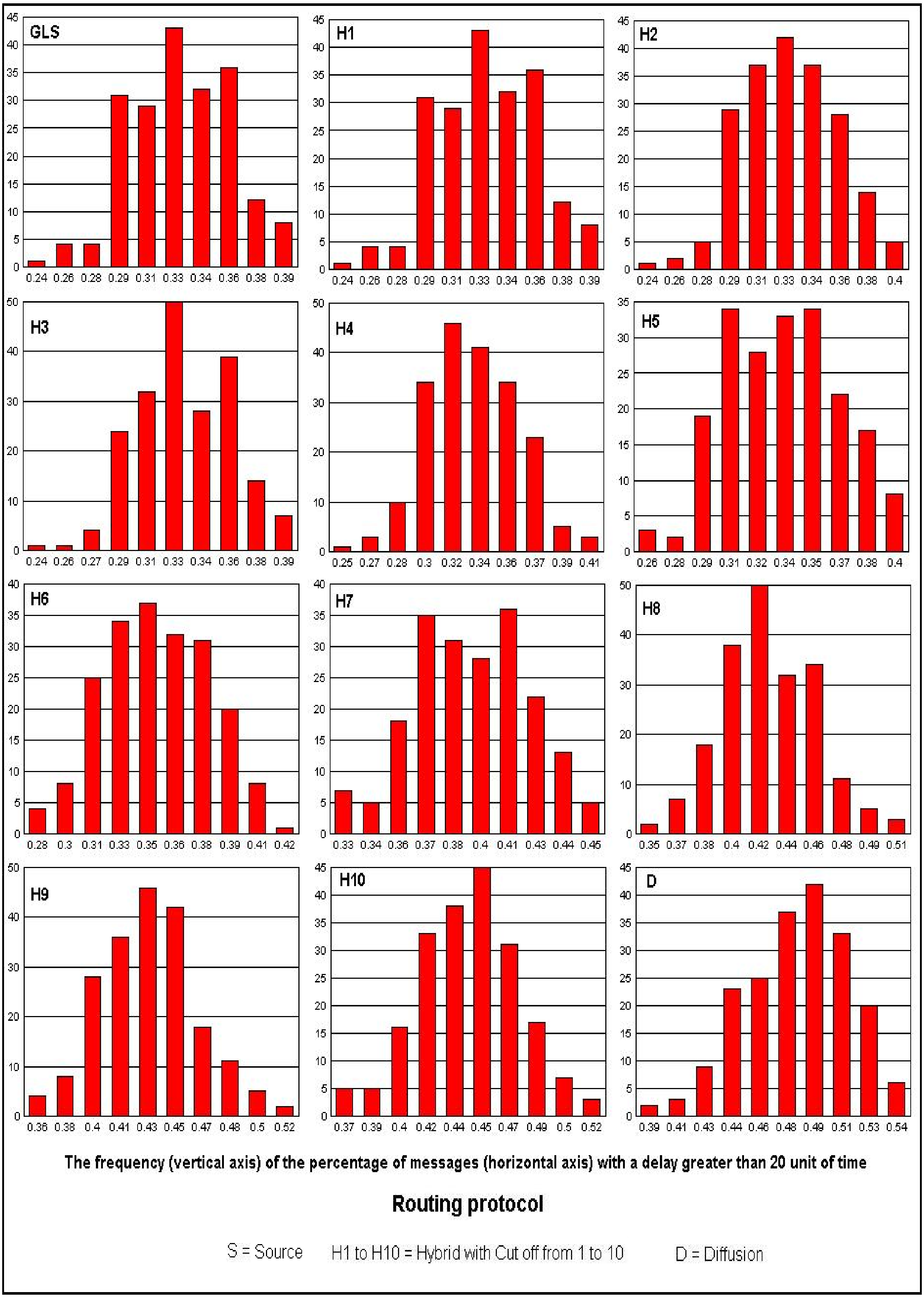


Fig. 6.22: Routing Protocols Delay greater than 20

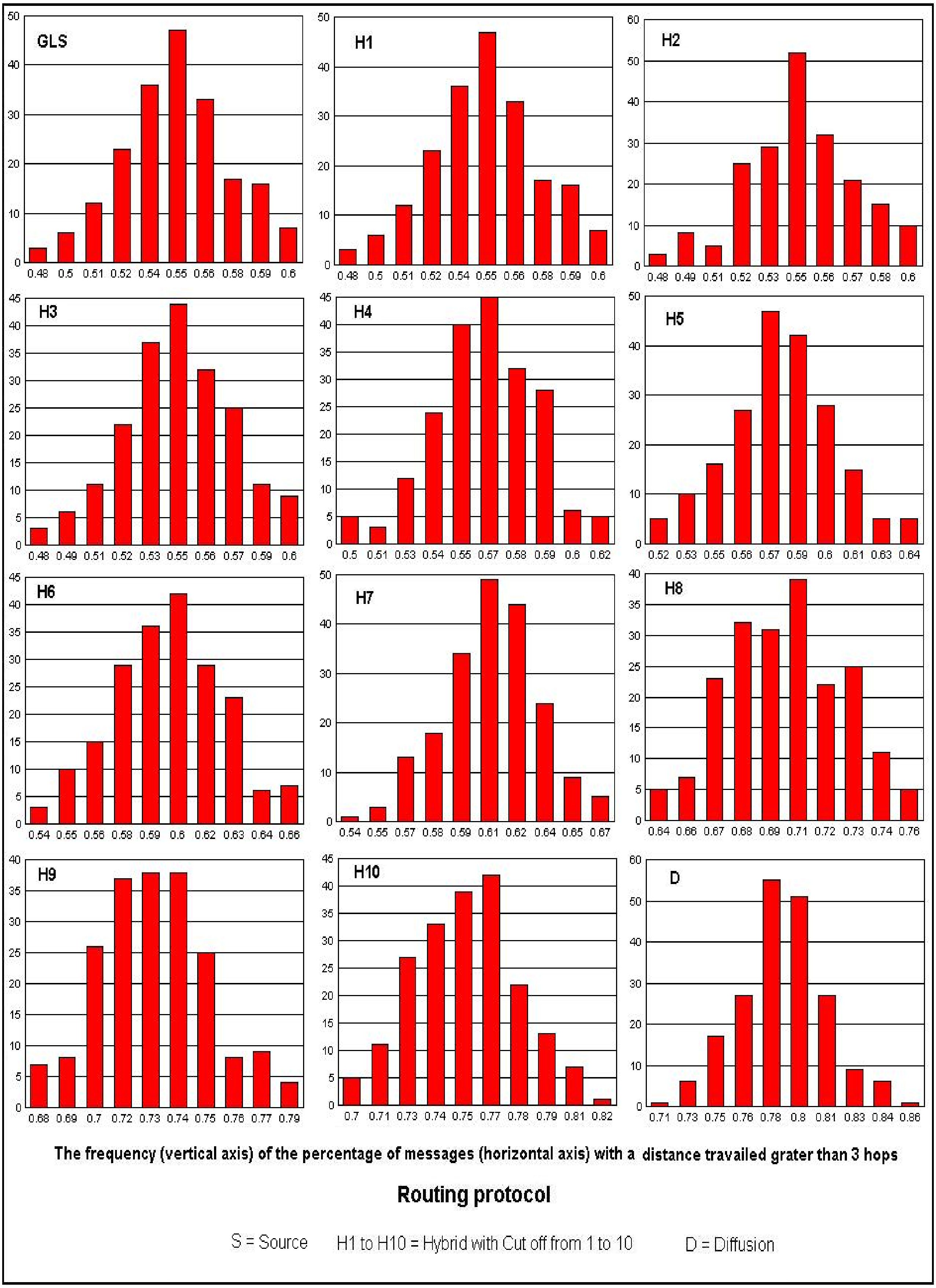
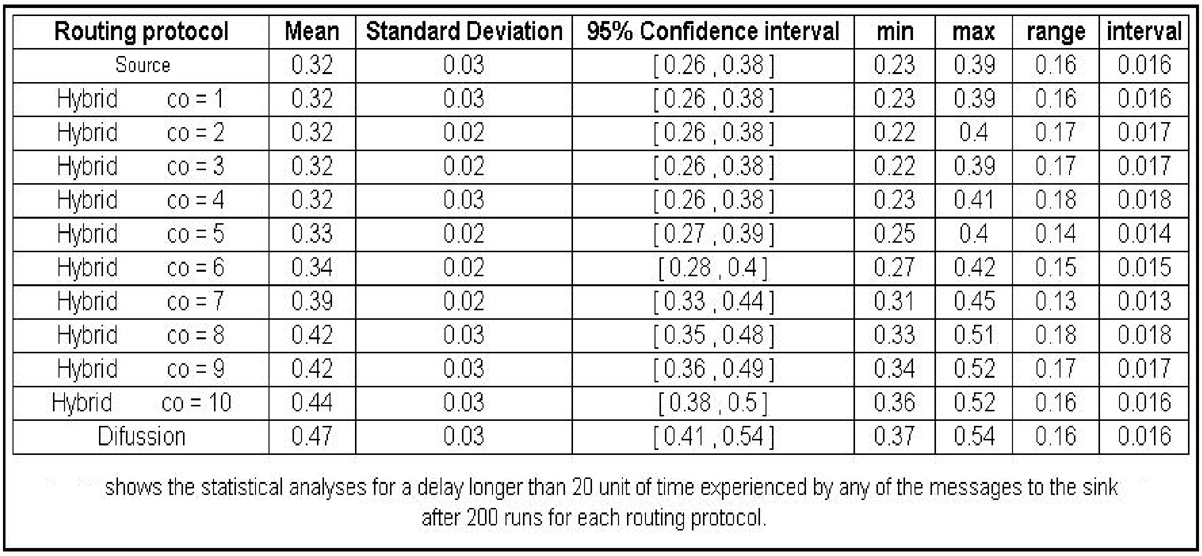


Fig. 6.23: Routing Protocols Distance greater than 3

Table 6.7 shows the Source Routing Protocol would have the shortest delay. Since, over 200 runs only 32% of the messages received by the sink would experience a delay greater than 20 unit of time. On the other hand, the Diffusion Routing Protocol would experience the longest delay. Since, over 200 runs 47% of the messages received by the sink would experience a delay greater than 20 unit of time. In the same time, messages routed by the Hybrid Routing Protocol would experience a delay time in between the delay time experienced by messages routed by the Source Routing protocol and the Diffusion Routing Protocol depends on the value of the cut off used by the Hybrid Routing Protocol. As the cut off value gets smaller, the Hybrid Routing Protocol would perform similar to the Source Routing Protocol and as the cut off value gets bigger; the Hybrid Routing Protocol would perform similar to the Diffusion Routing Protocol. Also, over the 200 runs, 23% to 39% of the messages routed by the Source Routing Protocol experienced a delay greater than 20 units of time. On the other hand, over the 200 runs, 37% to 54% of the messages routed by the Diffusion Routing Protocol experienced a delay greater than 20 units of time. In the same time, messages routed by the Hybrid Routing Protocol experienced a minimum and maximum percentage for a delay grater than 20 units of time in-betweens the ones experienced by messages routed by the Source Routing Protocol and the Diffusion Routing Protocol.

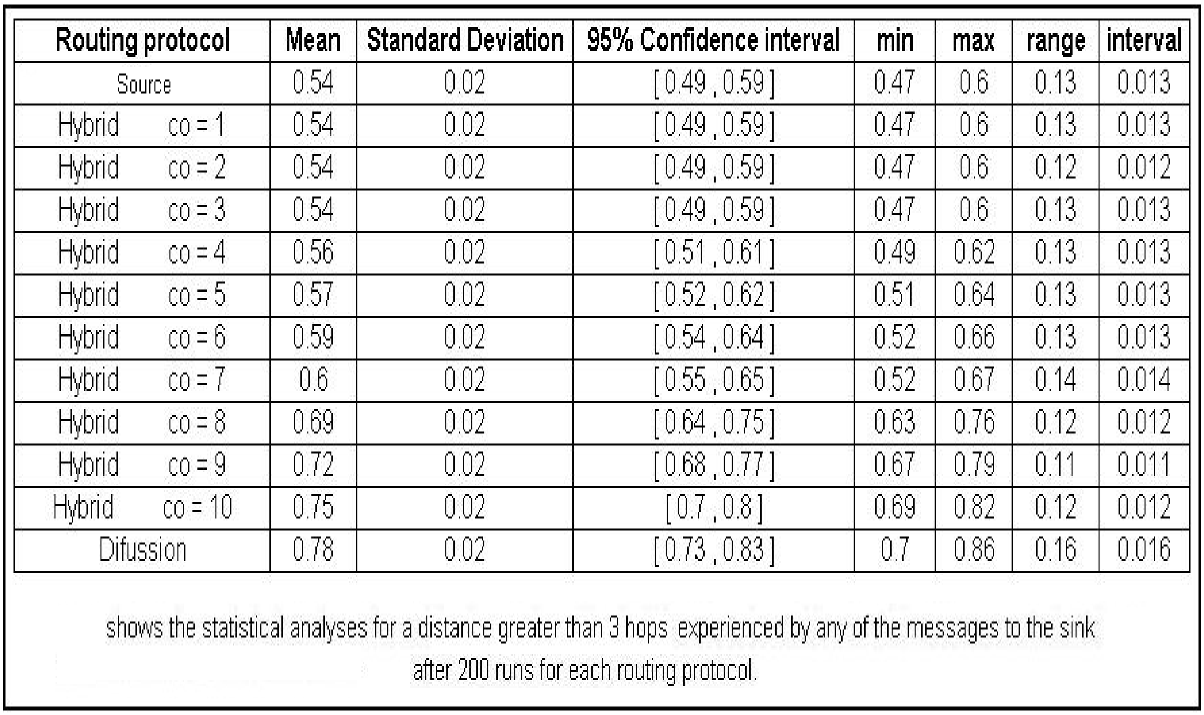


Routing protocol	Mean	Standard Deviation	95% Confidence interval	min	max	range	interval
Source	0.32	0.03	[0.26 , 0.38]	0.23	0.39	0.16	0.016
Hybrid co = 1	0.32	0.03	[0.26 , 0.38]	0.23	0.39	0.16	0.016
Hybrid co = 2	0.32	0.02	[0.26 , 0.38]	0.22	0.4	0.17	0.017
Hybrid co = 3	0.32	0.02	[0.26 , 0.38]	0.22	0.39	0.17	0.017
Hybrid co = 4	0.32	0.03	[0.26 , 0.38]	0.23	0.41	0.18	0.018
Hybrid co = 5	0.33	0.02	[0.27 , 0.39]	0.25	0.4	0.14	0.014
Hybrid co = 6	0.34	0.02	[0.28 , 0.4]	0.27	0.42	0.15	0.015
Hybrid co = 7	0.39	0.02	[0.33 , 0.44]	0.31	0.45	0.13	0.013
Hybrid co = 8	0.42	0.03	[0.35 , 0.48]	0.33	0.51	0.18	0.018
Hybrid co = 9	0.42	0.03	[0.36 , 0.49]	0.34	0.52	0.17	0.017
Hybrid co = 10	0.44	0.03	[0.38 , 0.5]	0.36	0.52	0.16	0.016
Difussion	0.47	0.03	[0.41 , 0.54]	0.37	0.54	0.16	0.016

shows the statistical analyses for a delay longer than 20 unit of time experienced by any of the messages to the sink after 200 runs for each routing protocol.

Table 6.7: Routing Protocols Statistics greater than 20

Table 6.8 shows the Source Routing Protocol would have the shortest distance to sink. Since, over 200 runs only 54% of the messages received by the sink would travels greater than 3 hops. On the other hand, the Diffusion Routing Protocol would experience the longest distance to sink. Since, over 200 runs 78% of the messages received by the sink would travels greater than 3 hops. In the same time, messages routed by the Hybrid Routing Protocol would experience a travailing distance that would be in between the travailing distance experienced by messages routed by the Source Routing Protocol and the Diffusion Routing Protocol depends on the value of the cut off used by the Hybrid Routing Protocol. As the cut off value gets smaller, the Hybrid Routing Protocol would perform similar to the Source Routing Protocol and as the cut off value gets bigger; the Hybrid Routing Protocol would perform similar to the Diffusion Routing Protocol. Also, over the 200 runs, 47% to 60% of the messages routed by the Source Routing Protocol experienced a travailing distance greater than 3 hops to the sink. On the other hand, over the 200 runs, 70% to 86% of the messages routed by the Diffusion Routing Protocol experienced a travailing distance greater than 3 hops to the sink. In the same time, messages routed by the Hybrid Routing Protocol experienced a minimum and maximum percentage for travailing distance grater than 3 hops to the sink in-betweens the ones experienced by messages routed by the Source Routing Protocol and the Diffusion Routing Protocol.



Routing protocol	Mean	Standard Deviation	95% Confidence interval	min	max	range	interval
Source	0.54	0.02	[0.49 , 0.59]	0.47	0.6	0.13	0.013
Hybrid co = 1	0.54	0.02	[0.49 , 0.59]	0.47	0.6	0.13	0.013
Hybrid co = 2	0.54	0.02	[0.49 , 0.59]	0.47	0.6	0.12	0.012
Hybrid co = 3	0.54	0.02	[0.49 , 0.59]	0.47	0.6	0.13	0.013
Hybrid co = 4	0.56	0.02	[0.51 , 0.61]	0.49	0.62	0.13	0.013
Hybrid co = 5	0.57	0.02	[0.52 , 0.62]	0.51	0.64	0.13	0.013
Hybrid co = 6	0.59	0.02	[0.54 , 0.64]	0.52	0.66	0.13	0.013
Hybrid co = 7	0.6	0.02	[0.55 , 0.65]	0.52	0.67	0.14	0.014
Hybrid co = 8	0.69	0.02	[0.64 , 0.75]	0.63	0.76	0.12	0.012
Hybrid co = 9	0.72	0.02	[0.68 , 0.77]	0.67	0.79	0.11	0.011
Hybrid co = 10	0.75	0.02	[0.7 , 0.8]	0.69	0.82	0.12	0.012
Difussion	0.78	0.02	[0.73 , 0.83]	0.7	0.86	0.16	0.016

shows the statistical analyses for a distance greater than 3 hops experienced by any of the messages to the sink after 200 runs for each routing protocol.

Table 6.8: Routing Protocols Statistics greater than 3

The reason why messages routed to the sink by each routing protocol would experience different delays is because the Diffusion Routing Protocol would only specify the next node on the path to the sink. So, the messages end up taking a longer path more often than the shortest path before it eventually reaches the sink. This is seen as advantage and disadvantage at the same time. It is an advantage because, the Diffusion Routing Protocol encourage multipath routing by distributing the load On longer routes to relief the shortest path route from forwarding the source node traffic load. Also, it is a disadvantage because; using the longer routs would mean the average number of hops per message delivery to the sink would increase. This means, the average message delay and the average power consumption per message delivery to the sink would increase. Yet, this is expected since the advantage of multipath routing would not come without a price to be paid in term of increased average number of hops per message delivery to the sink.

On the other hand, the Source Routing Protocol would specify the entire rout to the sink from the very beginning at the source node. Messages routed by the Source Routing Protocol experience a smaller average number of hopes to the sink per message delivery than messages routed by the Diffusion Routing Protocol. This means the shortest routs to the sink are more used by the Source Routing Protocol than longer rotes. In the same way, it is seen as an advantage and disadvantage in the same time. It is an advantage because, the QoS would improve and message delays would decrease. Also, the number of hopes and power consumption per message delivery to the sink would decrease. In the same time it is a disadvantage because, the multipath routing and smoothing out traffic over the WSN by selecting longer routs for message forwarding would decrease.

Chapter 7: Conclusions

7.1. Thesis Conclusion

The primary tool in finding multipath in prior studies [LOU05] and [GAL07] was the broadcast in Phase-One followed by the path sharing in Phase-Two of the Multipath Finding Protocol. As simulation shows, Phase-Two plays a smaller rule in promoting new paths between nodes to enhance multipath finding protocol compared to Phase-One. Simulation shows that Phase-One as it is stated in previous studies is quite extensive in finding a large number of total routes and most, if not all, of the primary unattached routes from every node to the sink. Yet, this comes at a heavy price of valuable network power. The power consumed in phase one would exponentially increase as the number of nodes increased. Also, most of the total routes found have to be deleted for unsuitability. Therefore, an expensive price is paid for lots of routes that are going to be deleted.

As this study is concerned, the network power is to be preserved for operation mode than to be consumed in Multipath Finding Protocol mode. So, adjustments were made to Phase-One of the Multipath Finding Protocol by choosing Type-Four broadcast. This resulted in significant savings in the over all network power. The network power savings techniques produced a much smaller number of total routes found, which none of them have to be deleted. Even though, the number of total routes found is much smaller after the changes made to Phase-One of the Multipath Finding Protocol. The results is 60% of the Primary Disjoined Paths from every node to the sink was found, compared to finding most of the Primary Disjoined Paths in previous studies.

After adjustments were made to Phase-One of the Multipath Finding Protocol in the way the broadcast is rebroadcast, the numbers of Primary Disjoined Paths discovered by each node were not significantly affected but the power consumption during the Multipath Finding Protocol was significantly reduced and the time needed to finish the Multipath Finding Protocol was significantly reduced as well.

The set up time for multipath routing over WSN runs reasonably fast. Multipath routing can achieve a balanced load among bottleneck nodes. It would allow for a better distribution of energy consumption. It takes into account the compromise between the involvement of as many nodes as possible and the discouragement of the use of long paths.

The Network Routing Efficiency in Type-Four Broadcast improved more than 3 times compared to Type-Three Broadcast. Even though, using either one of Type-Three or Type-Four Broadcast would result in finding 60% of the network Primary Disjoined Paths. The numeric value of the Network Routing Efficiency obtained by using Type-Four Broadcast means 37% of the routes used are the type of routes preferred and 63% of the routes are either Joined Paths or Parallel Paths. The Network Routing Efficiency could be improved up to 100% by deleting the unwanted routes. On the other hands, the Multipath Finding Protocol Efficiency cannot be changed for the network without changing the Multipath Finding Protocol.

Having the shortest path to the sink through every Layer-One node for every node in the network would lead to 100% Multipath Finding Protocol Efficiency. Also, a 100% Network Routing Efficiency would be obtained if no other routes to the sink were to be used other than the Primary Disjoined Paths. This would lead to an even division of the network routes between Layer-One nodes. Therefore, WSNs would have an even load distribution and a longer network lifetime.

It is important to keep the routes as untangled as possible through the nodes in the higher layers to divide the load equally between all Layer-One nodes. Yet it is less of a concern to have tangled or Joined Routes in the lower layers as nodes in lower layer are under used compared to nodes in higher layers. Also, nodes in lower layer would always last longer than nodes in higher layers. So, energy conservation is not an issue for lower layer nodes as they would always be the last to run out of power.

After changes were made to Phase-One of the Multipath Finding Protocol by switching from Type-Two Broadcast to Type-Four Broadcast, much smaller number of Joined Paths and Parallel Paths where discovered by the nodes compared to earlier studies [LOU05] and [GAL07]. Also, no Circular Paths and no Long Paths where discovered by any of the nodes. In comparison, the Multipath Finding Protocol in earlier studies [LOU05] and [GAL07] discovered circular paths then delete them from the routing tables.

The new equation to calculate the Residual Workload results in a better distribution of traffic on the WSN in a way that closely resemble the weight assigned to each rout.

The new equation would lead to a better handling of the WSN resources than the old equation would. This results in a smaller difference between the Expected and the Actual Workload. This results in a higher over all SWN efficiency.

Hybrid Routing Protocol does combine both of the advantages of Source Routing Protocol and Diffusion Routing Protocol. Also, the cut off value used in Hybrid Routing Protocol provides a control mechanism. It acts like a sliding bar control panel, the Hybrid Routing Protocol acts more like the Diffusion Routing Protocol as the cut off value are set to higher values. Also, the Hybrid Routing Protocol acts more like the Source Routing Protocol as its cut off value are set to lower values. This would give more flexibility for controlling the WSN performance.

Setting the cut off value to lower values would improve the QoS, reduce the average delay and average power consumption per message delivery to the sink. Also, it would decrease the average number of hops per message delivered to the sink. Yet, it would not diversify the paths used for communication and message forwarding.

On the other hand, setting the cut off value to higher values would increase the use of longer paths verses the shorter paths and improve multipath routing. Also, the average number of hops per message delivered to the sink would increase. This would degrade the QoS. Also, it would increase the average delay and average power consumption per message delivery to the sink compared to the case when the cut off value was set to lower values.

The route selection by Hybrid Routing would seek to smooth out traffic on the WSN, to optimize link capacity, to reduce message delays, to improve QoS and to extend battery life with emphases on all parameters at the same time. Improving multipath routing and smoothing traffic on the WSN would affect the QoS, link capacity, message delay, number of hops per message delivery to sink and battery life.

Hybrid Routing Protocol seeks to improve all parameter without significantly improving or degrading of one parameter over the others. Hybrid Routing Protocol offers to make a better route selection, for all messages on the WSN, than each of the Source Routing or Diffusion Routing being used alone.

Hybrid Routing encourages the participations of as many nodes as possible. Yet, discourage the use of long paths in the transmission of messages. Hybrid Routing is fixable and robust in determining the path selected to the sink for each message generated by a source node. Hybrid Routing is flexible and robust because, it allows the source node not to specify the complete path to the sink when there are not enough routs to choose from. Also, Hybrid Routing can adjust to achieve a balanced load distribution among bottleneck nodes.

7.2 Future Research Work

Further research could be in:

- Improving the network routing efficiency by locally analyzing the discovered routs to the sink and deleting non-primary disjoined routes.

- Improve the multipath finding protocol efficiency by developing better multipath finding protocol to find more Primary disjoined paths to the sink from every node without depleting the network limited power supply.

- The Multipath Finding Protocol could be improved by making changes to phase two of the Multipath Finding Protocol to make it more effective and richer in results. Phase two needs small portion of the network power and time. Thus, making it a good candidate for further exploration and experimentation. Modification and changes that could be made to phase two would have a good potential for further improvements to the Multipath Finding Protocol and to multipath routing on WSN. Phase two needs to be modified to introduce new primary unattached routes from all nodes to the sink.

- Broadcasting alone may not be the mechanism that would provide the most number of primary unattached routes for a small cost in terms of network power and time. Thus, different alternative methods of finding multipath routes are to be explored. For example, a collection of mechanisms working together could be the solution. As broadcasting alone would not provide the best-case scenario solution for the Multipath finding problem in WSN.

- Experimenting with different network sizes and topologies.

- Validating the mathematical framework for calculating the value of the Network hops factor (NHF) ß through simulations using different size and topology networks.

- Investigating the effect of redundancy and multipath routing in WSN when trade off between communication security and reliability are needed to be made in the case of optimizing the redundancy between communicating nodes.

References:

[AGH07] R. G. Aghaei, M. A. Rahman, W. Gueaieb and A. E. Saddik, "Ant Colony-Based Reinforcement Learning Algorithm for Routing in Wireless Sensor Networks", Proceedings on IEEE Instrumentation and Measurement Technology Conference (IMTC), Warsaw, Vol. 1, pp. 1-6, May 2007.

[ALK04] J. N. Al-Karaki, A. E. Kamal, “Routing Techniques in Wireless Sensor Networks: A Survey”, IEEE Wireless Communications, Vol. 11, No. 6, pp. 6-28, December 2004.

[ANT08] T. Antoine-Santoni, J. F. Santucci, E. De Gentili and B. Costa, “DEVS-WSN: A Discrete Event Approach for Wireless Sensor Network Simulation”, Proceedings on IEEE/ACS International Conference on Computer Systems and Applications (AICCSA), Doha, Vol. 1, pp. 895-898, March 2008.

[AYA93] E. Ayanoglu, I. Chih-Lin, R. D. Gitlin and J. E. Mazo, “Diversity Coding for Tansparent Self-Healing and Fault-Tolerant Communication Networks”, IEEE Transactions on Communications, Vol. 41, No. 11, pp. 1377-1386, May 1993.

[BAN02] S. Banerjee and A. Misra, “Minimum Energy Paths for Reliable Communication in Multi-Hop Wireless Networks”, Proceedings on 3rd ACM International Symposium on Mobile Ad Hoc Networking & Computing (MobiHoc), Vol. 1, pp. 146-156, June 2002.

[BAN96] A. Banerjea, “Simulation Study of the Capacity Effects of Dispersity Routing for Fault Tolerant Real-Time Channels”, Proceedings on ACM Applications, Technologies, Architectures, and Protocols for Computer Communications Conference (SIGCOMM), Vol. 26, No.4, pp 194-205, August 1996.

[BAU07] M. Baunach, R. Kolla and C. Mvihlberger, “Beyond Theory: Development of a Real World Localization Application as Low Power WSN”, Proceedings on 32nd IEEE Conference on Local Computer Networks (LCN), Dublin, Vol. 1, pp. 872-884, October 2007.

[BER04] P. Bergamo, D. Maniezzo, A. Travasoni, A. Giovanardi, G. Mazzini and M. Zorzi, “Distributed Power Control for Energy Efficient Routing in Ad Hoc Networks”, ACM Wireless Networks, Vol. 10, No. 1, pp. 29-42, January 2004.

[BHU10] G. S. Bhuyan, S. H. Mollah and N. Basher, “An Efficient Adaptive Multi-Hop Routing Protocol to Avoid Congestion for Wireless Sensor Networks”, Proceedings on 2nd IEEE Pacific-Asia Conference on Circuits, Communications and System (PACCS), Beijing, Vol. 1, pp. 315-318, August 2010.

[BLU07] J. Blumenthal, R. Grossmann, F. Golatowski and D. Timmermann, "Weighted Centroid Localization in Zigbee-Based Sensor Networks", Proceedings on IEEE International Symposium on Intelligent Signal Processing (WISP), Alcala de Henares, Vol. 1, pp. 1-6, October 2007.

[BOO08] P. Boonma and J. Suzuki, "MONSOON: A Coevolutionary Multiobjective Adaptation Framework for Dynamic Wireless Sensor Networks", Proceedings on 41st IEEE Annual Hawaii International Conference on System Sciences, Waikoloa, Vol. 1, pp.497-508, January 2008.

[CHA07] A.-C. Chang and C.-M. Chung, "Covariance Shaping Least-Squares Location Estimation Using TOA Measurements", ACM IEICE Transactions on Fundamentals of Electronics, Communications and Computer Sciences, Vol. E90-A, No. 3, pp. 691-693, March 2007.

[CHE10] Y. Chen, J. Cheng, H. Yang and B. Liu, “Research on a wireless sensor network's modulation based on ultra wideband signals”, Proceedings on IEEE International Conference on Computer, Mechatronics, Control and Electronic Engineering (CMCE), Changchun, Vol. 5, pp. 1-4, August 2010.

[CHI97] C.-C. Chiang, H.-K. Wu, W. Liu and M. Gerla, “Routing in Clustered Multihop, Mobile Wireless Networks with Fading Channel", Proceedings on IEEE Singapore International Conference on Networks, Singapore, Vol. 1, pp. 197-211, April 1997.

[COS07] A. Coso, U. Spagnolini and C. Ibars, ”Cooperative Distributed MIMO Channels in Wireless Sensor Networks”, IEEE Journal on Selected Areas in Communications, Vol. 25, No. 2, pp. 402-414, February 2007.

[CRU03] R. L. Cruz and A. V. Santhanam, “Optimal Routing, Link Scheduling and Power Control in Multi-hop Wireless Networks”, Proceedings on 22nd IEEE Annual Joint Conference of Computer and Communications Societies (INFOCOM), San Francisco, Vol. 1, pp. 101-117, March 2003.

[DUL03] S. Dulmann, T. Nieberg, J. Wu and P. Havinga, “Trade-Off between Traffic Overhead and Reliability in Multipath Routing for Wireless Sensor Networks”, Proceedings on IEEE Wireless Communications and Networking Conference (WCNC), New Orleans, Vol. 3, pp. 1918-1922, March 2003.

[GAL07] J. R. Gallardo, A. Gonzalez, L. Villasenor-Gonzalez and J. Sanchez, “Multipath Routing Using Generalized Load Sharing For Wireless Sensor Networks”, Proceedings on 7th IASTED Wireless and Optical Communications International Conferences (WOC), Montreal, Vol. 1, pp. 1-8, May 2007.

[GAN01] D. Ganesan, R. Govindan, S. Shenker, and D. Estrin, “Highly-Resilient, Energy-Efficient Multipath Routing in Wireless Sensor Networks”, Proceedings on

2nd ACM International Symposium on Mobile Ad Hoc Networking & Computing (MobiHoc), Vol. 1, pp. 251-254, October 2001.

[GUO08] K. Yu and Y. Guo, “Improved Positioning Algorithms for Nonline-of-Sight Environments”, IEEE Transactions on Vehicular Technology, Vol. 57, No. 4, pp. 2342-2353, July 2008.

[GUO10] L. Guo and Q. Tang, “An Improved Routing Protocol in WSN with Hybrid Genetic Algorithm”, Proceedings on 2nd IEEE International Conference on Networks Security Wireless Communications and Trusted Computing (NSWCTC), Wuhan, Vol. 2, pp. 289-292, April 2010.

[GUS97] E. Gustafsson and G. Karlsson, “A Literature Survey on Traffic Dispersion”, IEEE Networks, Vol. 11, No. 2, pp. 28-36, April 1997.

[GUT08] G. Gutierrez, B. Mejias, P. Van Roy, D. Velasco and J. Torres, “WSN and P2P: A Self-Managing Marriage”, Proceedings on 2nd IEEE International Conference on Self-Adaptive and Self-Organizing Systems Workshops (SASOW), Venice, Vol. 1, pp. 198-201, October 2008.

[HAN08] X. Han, Q. Haili, L. Xun and M. Hongxu, “Swarm Intelligence Based WSN-Mediated Distributed Multi-Robot Task Allocation”, Proceedings on 27th IEEE Chinese Control Conference (CCC), Kunming, Vol. 1, pp. 451-456, July 2008.

[HE10] L. He, “Efficient Multi-Path Routing in Wireless Sensor Networks”, Proceedings on 6th IEEE International Conference on Wireless Communications Networking and Mobile Computing (WiCOM), Chengdu, Vol. 1, pp. 1-4, September 2010.

[HEI00] W. R. Heinzelman, A. Chandrakasan and H. Balakrishnan, “Energy-Efficient Communication Protocol for Wireless Microsensor Networks”, Proceedings on 33rd

IEEE Annual Hawaii International Conference on System Sciences, Hawaii, Vol. 2, No. 10, pp. 174-185, January 2000.

[HEL04] A. Helmy, “CAPTURE: Location-Free Contact-Assisted Power-Efficient Query Resolution for Sensor Networks”, ACM SIGMOBILE Mobile Computing and Communications Review, Vol. 8, No. 1, pp. 27-47, January 2004.

[HON02] X. Hong, K. Xu and M. Gerla, “Scalable Routing Protocols for Mobile Ad Hoc Networks”, IEEE Network, Vol. 16, No. 4, pp. 11-21, August 2002.

[HUM08] D. Humphrey and M. Hedley, “Super-Resolution Time of Arrival for Indoor Localization”, Proceedings on IEEE International Conference on Communications (ICC), Beijing, Vol. 1, pp. 3286-3290, May 2008.

[JAI09] S. K. Jain and K. Garg, “A Hybrid Model of Defense Techniques against Base Station Jamming Attack in Wireless Sensor Networks”, Proceedings on 1st IEEE International Conference on Computational Intelligence, Communication Systems and Networks (CICSYN), Indore, Vol. 1, pp. 102-107, July 2009.

[JUN06] J. K. Juntunen, M. Kuorilehto, M. Kohvakka, V. A. Kaseva, M. Hannikainen and T. D. Hamalainen, “WSN API: Application Programming Interface for Wireless Sensor Networks”, Proceedings on 17th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, Helsinki, Vol. 1, pp. 1-5, September 2006.

[KAN08] T. Kandasamy and J. K. Krishnan, “Using Multipath Priority Routing for Solar Powered Wireless Sensor Networks”, Proceedings on IEEE International Symposium on Information Technology (ITSim), Kuala Lumpur, Vol. 4, pp. 1-6, August 2008.

[KEN10] J. Kenyeres, S. Sajban, P. Farkas and M. Rakus, “Indoor Experiment with WSN Application”, Proceedings on 33rd IEEE International Convention MIPRO, Opatija, Vol. 1, pp. 863-866, May 2010.

[KOS08] S. Kostin, L. B. de Pinho and C. L. de Amorim, “Transmission Power Levels Prediction for Distributed Topology Control Protocols within Parameterized Scenarios”, Proceedings on IEEE International Conference on Telecommunications (ICT), St. Petersburg, Vol. 1, pp. 1-7, June 2008.

[LEE01] S.-J. Lee and M. Gerla, “Split Multipath Routing with Maximally Disjoint Paths in Ad hoc Networks”, Proceedings on IEEE International Conference on Communications (ICC), Helsinki, Vol. 10, pp. 3201-3205, June 2001.

[LEE99] S.-W. Lee and C.-S. Wu, “A k-Best Paths Algorithm for Highly Reliable Communication Networks”, IEICE Transactions on Communications, Vol. E82-B, pp. 586-590, June 1999.

[LEI09] Y. Lei, “Research and Implementation of WSN-Based Data Acquisition and Analysis System Using Agent Collaboration”, Proceedings on 2nd IEEE International Conference on Power Electronics and Intelligent Transportation System (PEITS), Shenzhen, Vol. 3, pp. 235-237, December 2009.

[LEU06] K.–C. Leung and V. O. K. Li, “Generalized Load Sharing for Packet-Switching Networks I: Theory and Packet-Based Algorithm”, IEEE Transactions on Parallel and Distributed Systems, Vol. 17, No. 7, pp. 694-702, July 2006.

[LI01] Q. Li, J. Aslam and D. Rus, “Online Power-Aware Routing in Wireless Ad-Hoc Networks”, Proceedings on 7th ACM Annual International Conference on Mobile Computing and Networking (MobiCom), Vol. 1, pp.97-107, July 2001.

[LOU05A] W. Lou, W. Liu and Y. Zhang, “Performance Optimization using Multipath Routing in Mobile Ad Hoc and Wireless Sensor Networks”, Combinatorial Optimization in Communication Networks, Kluwer Academic Publishers, 2005.

[LOU05B] W. Lou, “An Efficient N-to-1 Multipath Routing Protocol in Wireless Sensor Networks”, Proceedings on IEEE International Conference on Mobile Ad-hoc and Sensor Systems, Washington, Vol. 1, pp. 8-18, November 2005.

[MAX75] N. F. Maxemchuk, “Dispersity routing”, Proceedings on IEEE International Conference on Communications (ICC), Vol. 41, pp. 10-13, June 1975.

[MEN09] M. L. Mendoza and V. H. Z. Silva, “Self-Protection Strategies in WSN Using Geometrical Arrays of Directional Antennas and Incremental RSSI Measuments”, Proceedings on 1st IEEE International Conference on Computational Intelligence, Communication Systems and Networks (CICSYN), Indore, Vol. 1, pp. 131-136, July 2009.

[MOH09] P. Mohanty, S. Panigrahi, N. Sarma and S. S. Satapathy, “A Symmetric Key Based Secured Data Gathering Protocol for WSN”, Proceedings on 3rd IEEE International Conference on Anti-Counterfeiting, Security and Identification in Communication (ASID), Hong Kong, Vol. 1, pp. 138-143, August 2009.

[NAS02] A. Nasipuri, R. Castaneda and S. R. Das, “Performance of Multipath Routing for On-Demand Protocols in Ad Hoc Networks”, IEEE Mobile Networks and Applications, Vol. 6, No. 4, pp. 339-349, November 2002.

[NAS99] A. Nasipuri and S. R. Das, “On-Demand Multipath Routing for Mobile Ad-Hoc Networks”, Proceedings on 8th IEEE International Conference on Computer Communications and Networks, Boston, Vol. 1, pp. 64-70, October 1999.

[OGI89] R. Ogier and N. Shacham, “A Distributed Algorithm for Finding Shortest Pairs of Disjoint Paths”, Proceedings on 8th IEEE Annual Joint Conference of

Computer and Communications Societies Technology: Emerging or Converging (INFOCOM), Ottawa, Vol. 1, pp. 173-182, April 1989.

[PAB09] M. González, M. Sánchez-Fernández, A. Armada and S. Morosi, "Performance study of cooperative diversity schemes for Wireless Sensor Networks based on Ultra Wide Band", Proceedings on 1st IEEE International Conference on Wireless Communication, Vehicular Technology, Information Theory and Aerospace & Electronic Systems Technology (VITAE), Aalborg, Vol. 1, pp. 777-781, May 2009.

[PAP02] P. Papadimitratos, Z. Haas and E. G. Sirer. "Path-Set Selection in Mobile Ad Hoc Networks", Proceedings on 3rd ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc), Vol. 1, pp. 1-11, June 2002.

[PAR93] A. K. Parekh and R. G. Gallager, "A Generalized Processor Sharing Approach to Flow Control in Integrated Services Networks: The Single-Node Case", IEEE/ACM Transactions on Networking, Vol. 1, No. 3, pp. 344-357, June 1993.

[PAR97] V. D. Park and M. S. Corson, "A Highly Adaptive Distributed Routing Algorithm for Mobile Wireless Networks", Proceedings on 16th IEEE Annual Joint Conference on Computer and Communications Societies (INFOCOM), Kobe, Vol. 3, pp. 1405-1413, April 1997.

[PEA00] M. R. Pearlman, Z. J. Haas, P. Sholander and S. S. Tabrizi, "On the Impact of Alternate Path Routing for Load Balancing in Mobile Ad Hoc Networks", Proceedings on 1st IEEE/ACM Annual Workshop on Mobile and Ad Hoc Networking and Computing (MobiHOC), Boston, Vol. 1, pp. 3-10, August 2000.

[PEI99] G. Pei, M. Gerla, X. Hong and C.-C. Chiang, "A Wireless Hierarchical Routing Protocol with Group Mobility", Proceedings on IEEE Wireless

Communications and Networking Conference (WCNC), New Orleans, Vol. 3, pp. 1538-1542, September 1999.

[PHA03] P. P. Pham and S. Perreau, “Performance Analysis of Reactive Shortest Path and Multipath Routing Mechanism With Load Balance”, Proceedings on 22nd IEEE Societies Annual Joint Conference of IEEE Computer and Communications (INFOCOM), Vol. 1, pp. 251-259, March 2003.

[POO10] S. Poojary and M. Pai , “Multipath Data Transfer in Wireless Multimedia Sensor Network”, Proceedings on IEEE International Conference on Broadband, Wireless Computing, Communication and Applications (BWCCA), Fukuoka, Vol. 1, pp. 379-383, November 2010.

[QIA03] S. De, C. Qiao and H. Wu, “Meshed Multipath Routing: An Efficient Strategy in Sensor Networks”, Proceedings on IEEE Wireless Communications and Networking Conference (WCNC), New Orleans, Vol. 3, pp. 1912-1917, March 2003.

[SAF03A] A. Safwat, H. Hassanein and H. Mouftah, “A Framework for Wireless Ad Hoc Networks with a Quasi-Guaranteed Minimum System Lifetime”, Proceedings on 8th IEEE International Symposium on Computers and Communications (ISCC), Vol. 1, pp. 349-355, July 2003.

[SAF03B] A. Safwat, H. Hassanein and H. Mouftah, “Q-GSL: A Framework for Energy-Conserving Wireless Multi-Hop Ad hoc Networks”, Proceedings on IEEE International Conference on Communications (ICC), Vol. 2, pp. 1101-1107, May 2003.

[SAT09] T. Sathyan, D. Humphrey and M. Hedley, “Target Tracking in Multipath Environments—An Algorithm Inspired by Data Association”, Proceedings on 12th IEEE International Conference on Information Fusion (FUSION), Seattle, Vol. 1, pp. 1650-1657, July 2009.

[SER10] C. Sergiou and V. Vassiliou, “Energy Utilization of HTAP under Specific Node Placements in Wireless Sensor Networks”, Proceedings on IEEE European Wireless Conference (EW), Lucca, Vol. 1, pp. 482-487, April 2010.

[SHA02] R. C. Shah and J. M. Rabaey, “Energy Aware Routing for Low Energy Ad Hoc Sensor Networks”, Proceedings on IEEE Wireless Communications and Networking Conference (WCNC), Vol. 1, pp. 350-355, March 2002.

[SHU08] L. Shu, Y. Zhang, L.T. Yang, Y. Wang, M. Hauswirth and N. Xiong, “Geographic Routing in Wireless Multimedia Sensor Networks”, Proceedings on 2nd IEEE International Conference on Future Generation Communication and Networking (FGCN), Hainan Island, Vol. 1, pp. 68-73, December 2008.

[SHU10] L. Shu, Z. Yuan, T. Hara, L. Wang and Y. Zhang, “Impacts of Duty-Cycle on TPGF Geographical Multipath Routing in Wireless Sensor Networks”, Proceedings on 18th IEEE International Workshop on Quality of Service (IWQoS), Beijing, Vol. 1, pp. 1-2, June 2010.

[SID91] D. Sidhu, R. Nair and S. Abdallah, “Finding Disjoint Paths in Networks”, Proceedings on ACM Conference on Communications architecture & protocols (SIGCOMM), Vol. 1, pp. 43-51, August 1991.

[SIN98] S. Singh, M. Woo and C.S. Raghavendra, “Power Aware Routing in Mobile Ad Hoc Networks”, Proceedings on 4th ACM/IEEE Annual International Conference on Mobile Computing and Networking (MobiCom), Vol. 1, pp. 181-190, October 1998.

[SIV98] R. Sivakumar, B. Das and V. Bharghavan, “The Clade Vertebrata: Spines and Routing in Ad Hoc Networks”, Proceedings on 3rd IEEE Symposium on Computer Communications (ISCC), Athens, Vol. 1, pp. 599-605, June 1998.

[SOH00] K. Sohrabi, J. Gao, V. Ailawadhi and G. J. Pottie, “Protocols for Self-Organization of a Wireless Sensor Network”, IEEE Personal Communications, Vol. 7, No. 5, pp. 16-27, October 2000.

[SRI02] V. Srinivasan, C. F. Chiasserini, P. Nuggehalli and R. R. Rao, “Optimal Rate Allocation and Traffic Splits for Energy Efficient Routing in Ad Hoc Networks”, Proceedings on 21st IEEE Annual Joint Conference of Computer and Communications Societies (INFOCOM), Vol. 2, pp. 950-957, November 2002.

[STO07] T. Stoyanova, F. Kerasiotis, A. Prayati and G. Papadopoulos, “Evaluation of Impact Factors on RSS Accuracy for Localization and Tracking Application”, Proceedings on 5th ACM International Workshop on Mobility Management and Wireless Access (MobiWac), Vol. 1, pp. 9-16, October 2007.

[TEJ09] S. Tejaswi and R. Garimella, “Meshed multipath routing with leveling in Route Discovery: An efficient strategy in wireless sensor networks”, Proceedings on 4th IEEE International Symposium on Wireless Pervasive Computing (ISWPC), Melbourne, Vol. 1, pp. 1-5, February 2009.

[TEO08] J.-Y. Teo, Y. Ha and C.-K. Tham, “Interference-Minimized Multipath Routing with Congestion Control in Wireless Sensor Network for High-Rate Streaming”, IEEE Transactions on Mobile Computing, Vol. 7, No. 9, pp. 1124-1137, September 2008.

[TRA08] C. Tran-Xuan, E.-C. Kim and I. Koo, "RSS Based Localization Scheme Using Angle-Referred Calibration in Wireless Sensor Networks", Proceedings on 4th ACM International Conference on Intelligent Computing (ICIC), Vol. 1, pp. 1222-1233, September 2008.

[TRA09] C. Tran-Xuan, V.-H. Vu and I. Koo, “Calibration Mechanism for RSS Based Localization Method in Wireless Sensor Networks”, Proceedings on 11th IEEE

International Conference on Advanced Communication Technology (ICACT), Phoenix Park, Vol. 1, pp. 560-563, February 2009.

[TSI01] A. Tsirigos and Z. J. Haas, “Multipath Routing in the Presence of Frequent Topological Changes”, IEEE Communication Magazine, Vol. 39, No. 11, pp. 132-138, November 2001.

[USS09] T. Ussmueller, M. Jung and R. Weigel, “Synthesizer Concepts for FMCW Based Locatable Wireless Sensor Nodes”, Proceedings on IEEE International Microwave Workshop on Wireless Sensing, Local Positioning and RFID (IMWS), Cavtat, Vol. 1, pp. 1-4, September 2009.

[VAL03] A. Valera, W. K. G. Seah, and SV. Rao, “Cooperative Packet Caching and Shortest Multipath Routing in Mobile Ad hoc Networks”, Proceedings on 22nd IEEE Societies Annual Joint Conference on Computer and Communications (INFOCOM), Vol. 1, pp. 260-269, March 2003.

[VAR08] S. Varma, U.S. Tiwary, A. Jain and T. Sharma, “Statistical Energy Efficient Multipath Routing Protocol”, Proceedings on IEEE International Conference on Information Networking (ICOIN), Busan, Vol. 1, pp. 1-5, January 2008.

[WAN03] X. Wang, G. Xing, Y. Zhang, C. Lu, R. Pless and C. Gill, “Integrated Coverage and Connectivity Configuration in Wireless Sensor Networks”, Proceedings on 1st ACM International Conference on Embedded Networked Sensor Systems (SenSys), Vol. 1, pp. 28-39, November 2003.

[WAN09] W. Wang, T. Huang, H. Liu and F. Pang, “Localization algorithm based on SVM-Data Fusion in wireless sensor networks”, Proceedings on 3rd IEEE International Conference on Genetic and Evolutionary Computing (WGEC), Guilin, Vol. 1, pp. 447-450, October 2009.

[WAN10] W.-W. Wang, L.-S. Hong, G.-M. Zhang and B.-Z. Wang, “Node Localization Based on Time Reversal in Wireless Sensor Network”, Proceedings on IEEE International Conference on Microwave and Millimeter Wave Technology (ICMMT), Chengdu, Vol. 1, pp. 81-83, May 2010.

[WEI09] W. Wei-hong, C. Yi-ling and C. Tie-ming, “Design and Implementation of an ECDSA-Based Identity Authentication Protocol on WSN”, Proceedings on 3rd IEEE International Symposium on Microwave, Antenna, Propagation and EMC Technologies for Wireless Communications, Beijing, Vol. 1, pp. 1202-1205, October 2009.

[WIL02] A. Willig, R. Shah, J. Rabaey and A. Wolisz, “Altruists in the PicoRadio Sensor Network”, Proceedings on 4th IEEE International Workshop on Factory Communication Systems, Vol. 1, pp. 175-184, August 2002.

[XIA08] X. Xian, W. Shi and H. Huang, “Comparison of OMNET++ and Other Simulator for WSN Simulation”, Proceedings on 3rd IEEE Conference on Industrial Electronics and Applications (ICIEA), Singapore, Vol. 1, pp. 1439-1443, June 2008.

[XIA10] Y. Xiao, X. Cui, H. Li and T. Xi, “A Protocol Simplifying Mechanism for a WSN Module”, Proceedings on IEEE International Conference on Electronics and Information Engineering (ICEIE), Kyoto, Vol. 2, pp. 474-477, August 2010.

[YOU10] J. Youssef, B. Denis, C. Godin and S. Lesecq, ”New TOA Estimators within Energy-Based Receivers Under Realistic UWB Channel Statistics”, Proceedings on 71st IEEE Vehicular Technology Conference (VTC), Taipei, Vol. 1, pp. 1-5, May 2010.

[YUS09] K. M. Yusof , J. Woods and S. Fitz, “Frequency Scanning Using Software Defined Radio for Localised Range Estimation”, Proceedings on 3rd IEEE

International Conference on Sensor Technologies and Applications (SENSORCOMM), Athens, Vol. 1, pp. 181-186, June 2009.

[ZHA08] Y. Zhang, L. Zhang and X. Shan, “Ranking-Based Statistical Localization for Wireless Sensor Networks”, Proceedings on IEEE Wireless Communications and Networking Conference (WCNC), Las Vegas, Vol. 1, pp. 2561-2566, April 2008.

[ZHA10] W. Zhang, Q. Yin, X. Feng and W. Wang, “Distributed TDoA Estimation for Wireless Sensor Networks Based on Frequency-Hopping in Multipath Environment”, Proceedings on 71st IEEE Vehicular Technology Conference (VTC), Taipei, Vol. 1, pp. 1-5, May 2010.

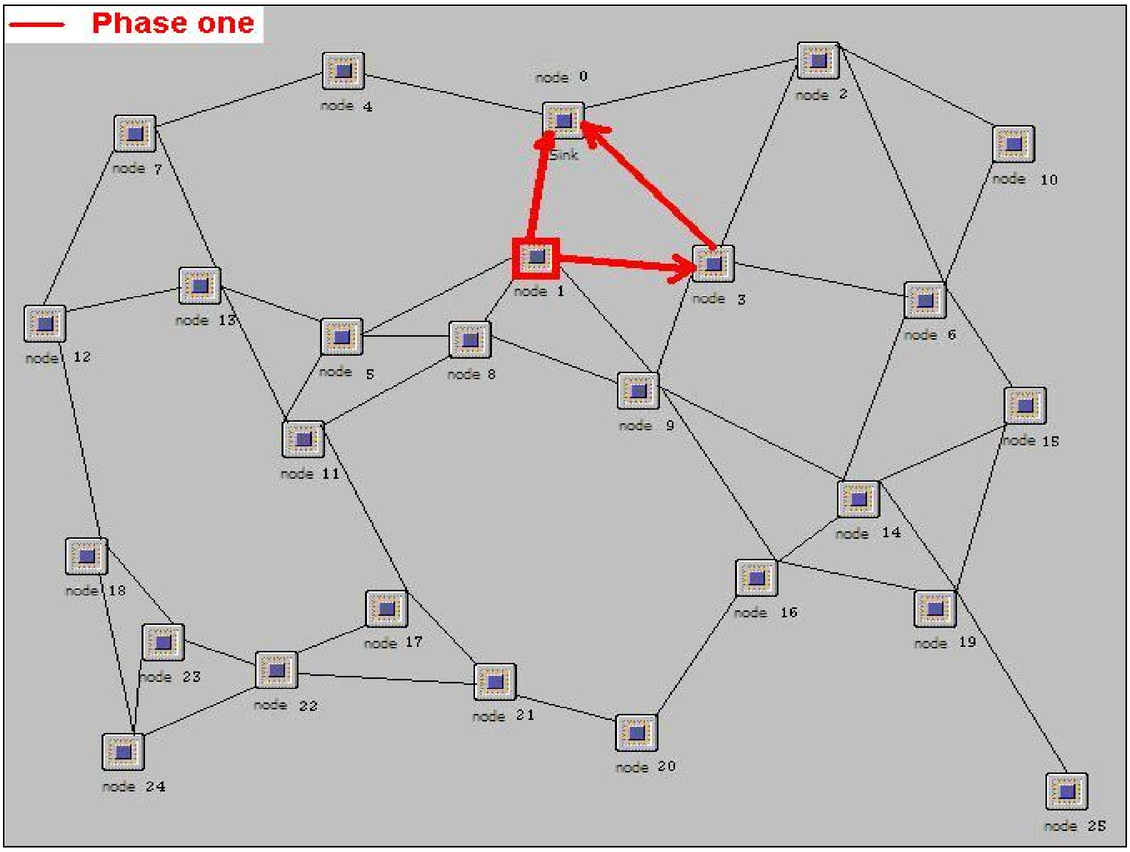
[ZHE04] J. Zheng and M. J. Lee, “Will IEEE 802.15.4 Make Ubiquitous Networking a Reality?: A Discussion on a Potential Low Power, Low Bit Rate Standard”, IEEE Communications Magazine, Vol. 42, No. 6, pp. 140-146, June 2004.

[ZHE06] W. Ji, B.-y. Zheng, “A Novel Cooperative MAC Protocol for WSN Based on NDMA”, Proceedings on 8th IEEE International Conference on Signal Processing, Beijing, Vol. 4, pp. 1-8, November 2006.

Appendix A: Routes Discovered

Appendix A shows a graphical representation of the routes discovered using the Multipath Finding Protocol developed in this thesis for the WSN used for simulation.

The paths promoted through the network are the Primary Disjoined Paths (shortest paths). Also, Parallel Paths would be discovered and promoted. But, it is not as often in Type-Four Broadcast, as it is the case in Type-Three Broadcast. This is due to the fewer number of rebroadcasts made by each node in Phase-One of the Multipath Finding Protocol when Type-Four Broadcast is used compared to using Type-Three Broadcast. In the same time, no Duplicated or Circular or Long paths would be discovered or promoted.



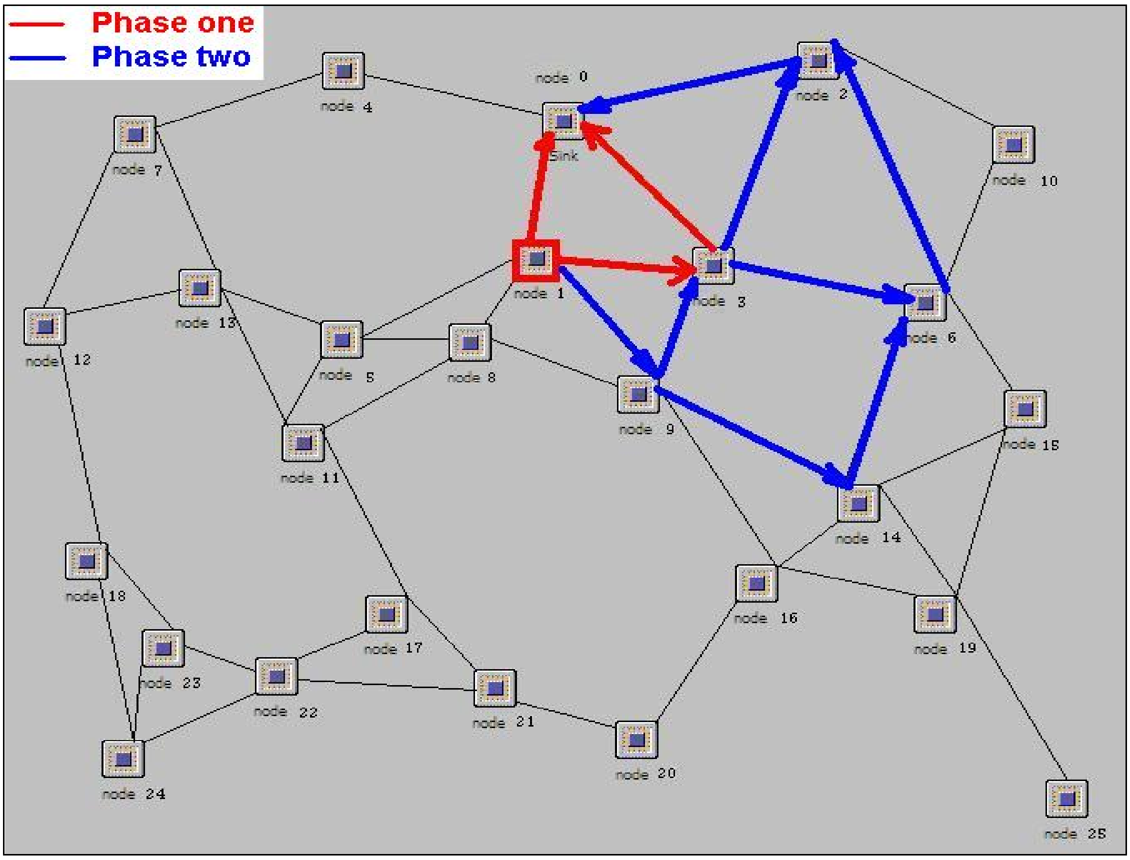


Fig. A.1: Routes discovered by node 1

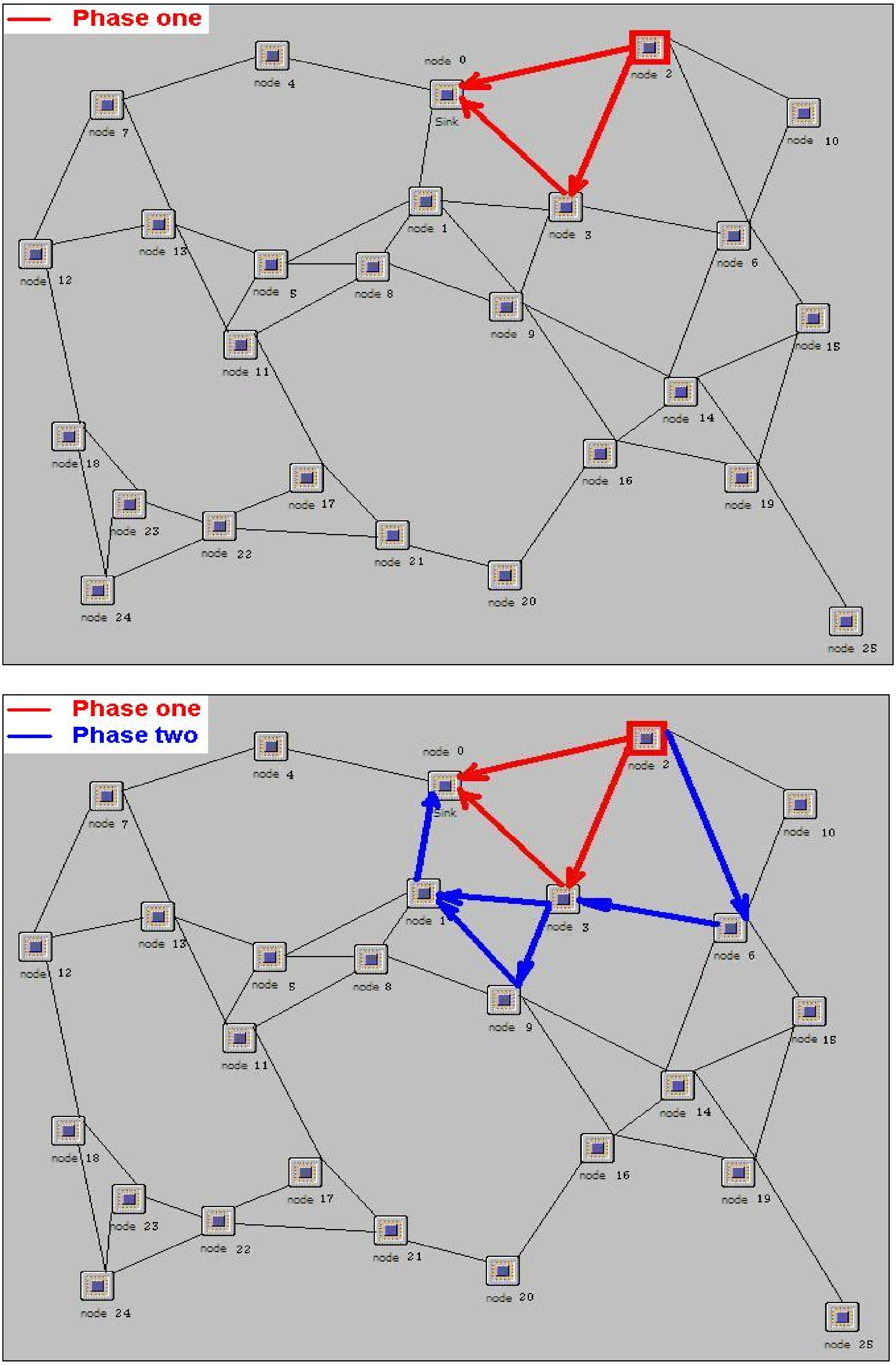


Fig. A.2: Routes discovered by node 2

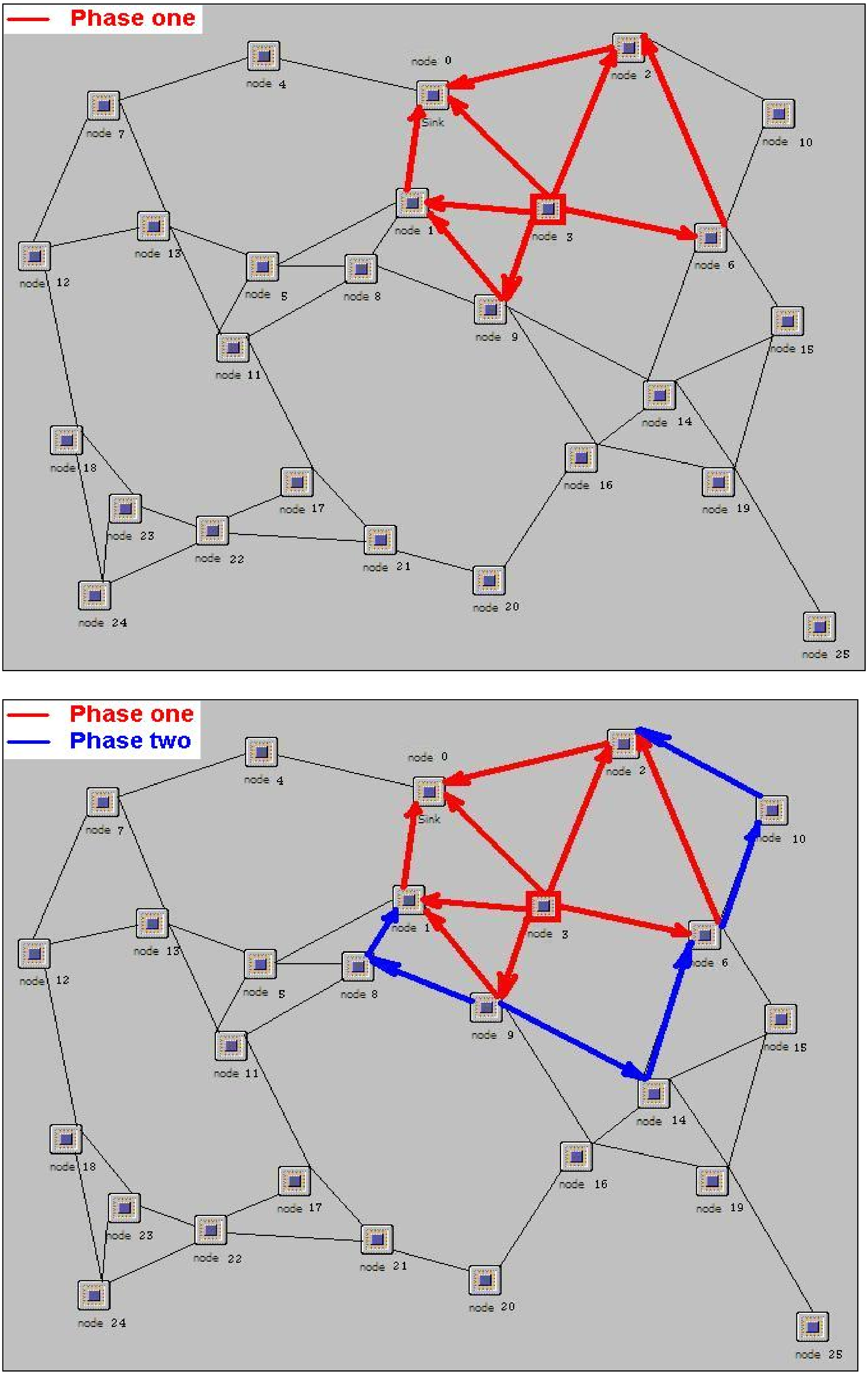


Fig. A.3: Routes discovered by node 3

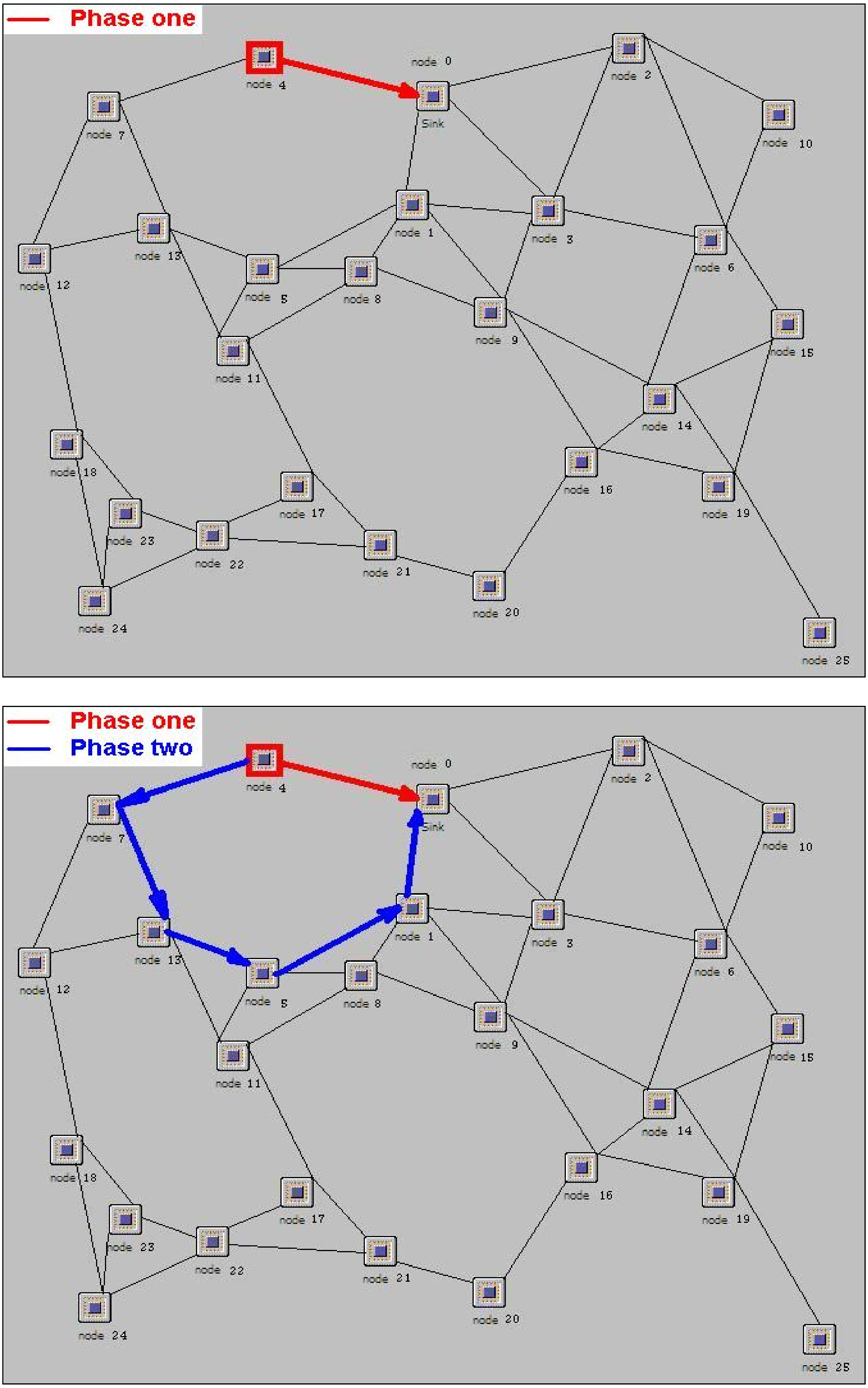


Fig. A.4: Routes discovered by node 4

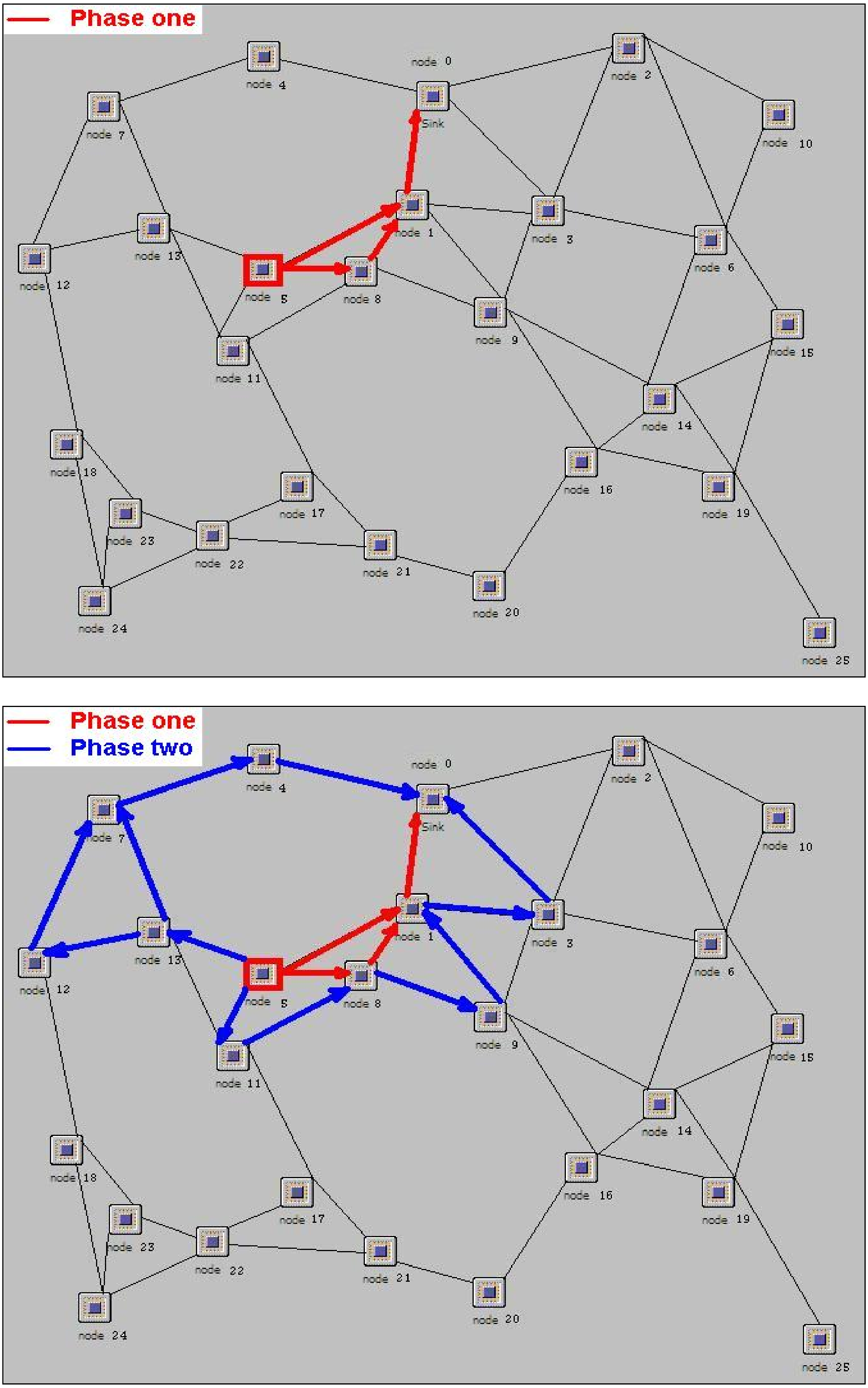


Fig. A.5: Routes discovered by node 5

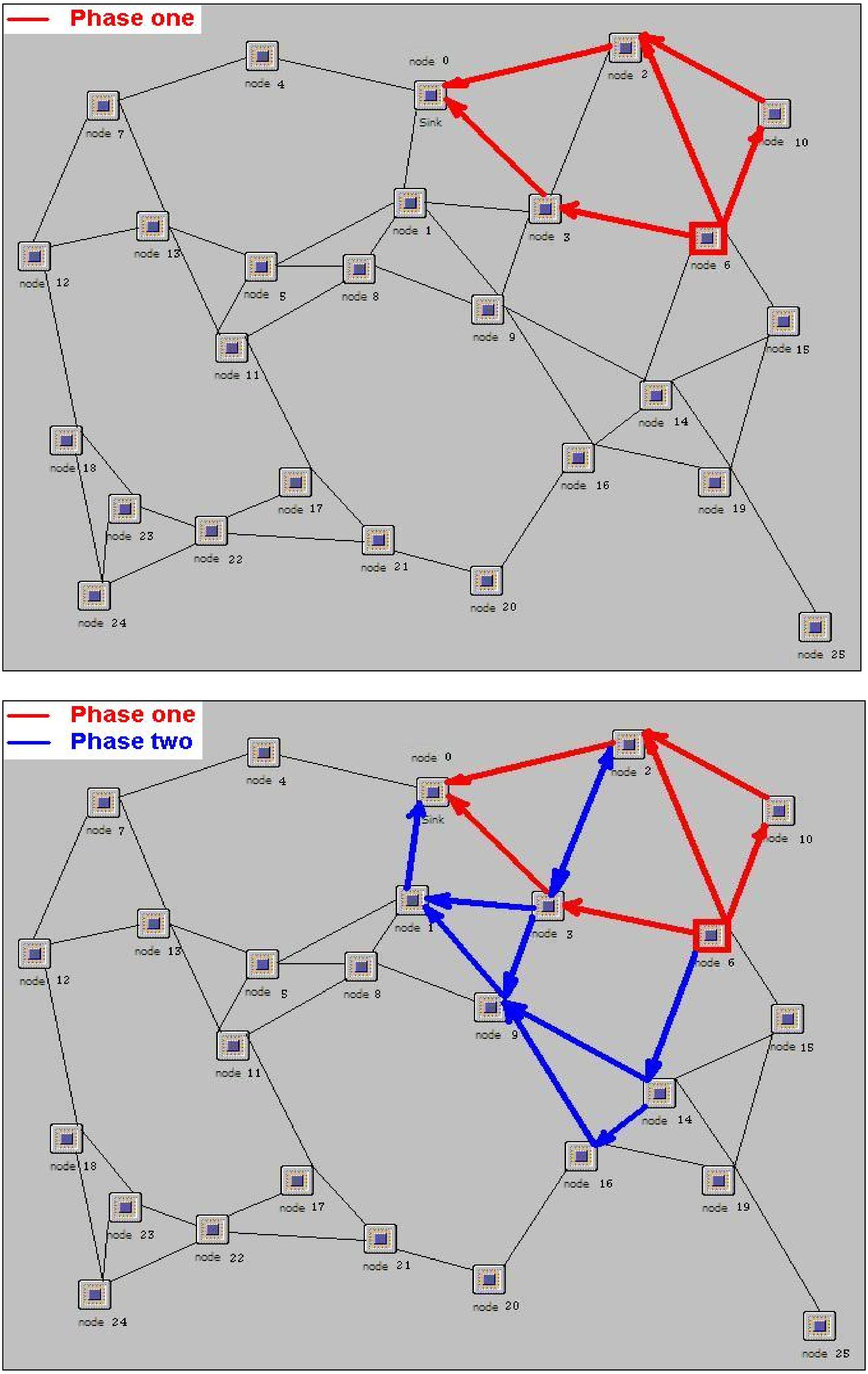


Fig. A.6: Routes discovered by node 6

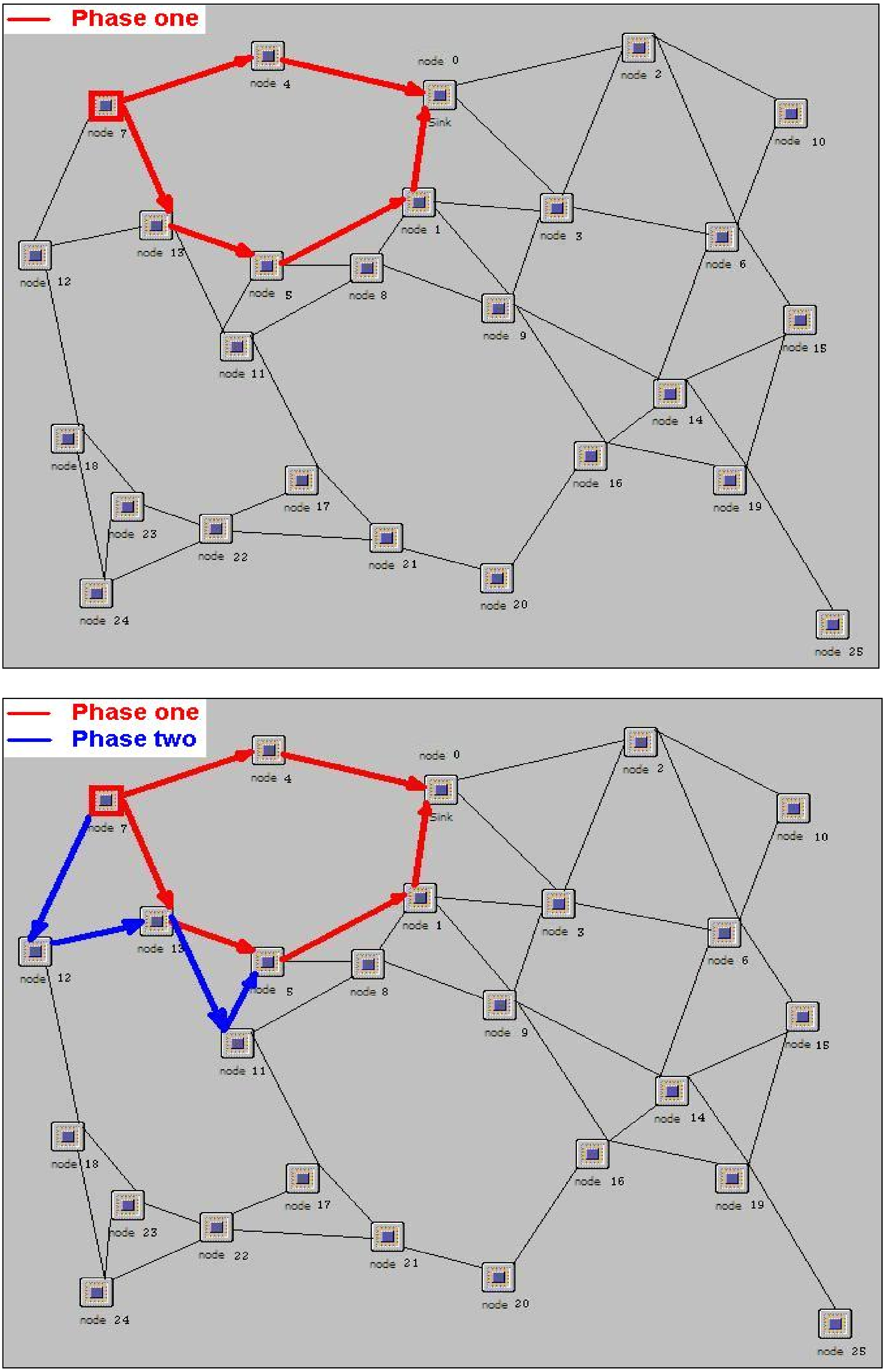


Fig. A.7: Routes discovered by node 7

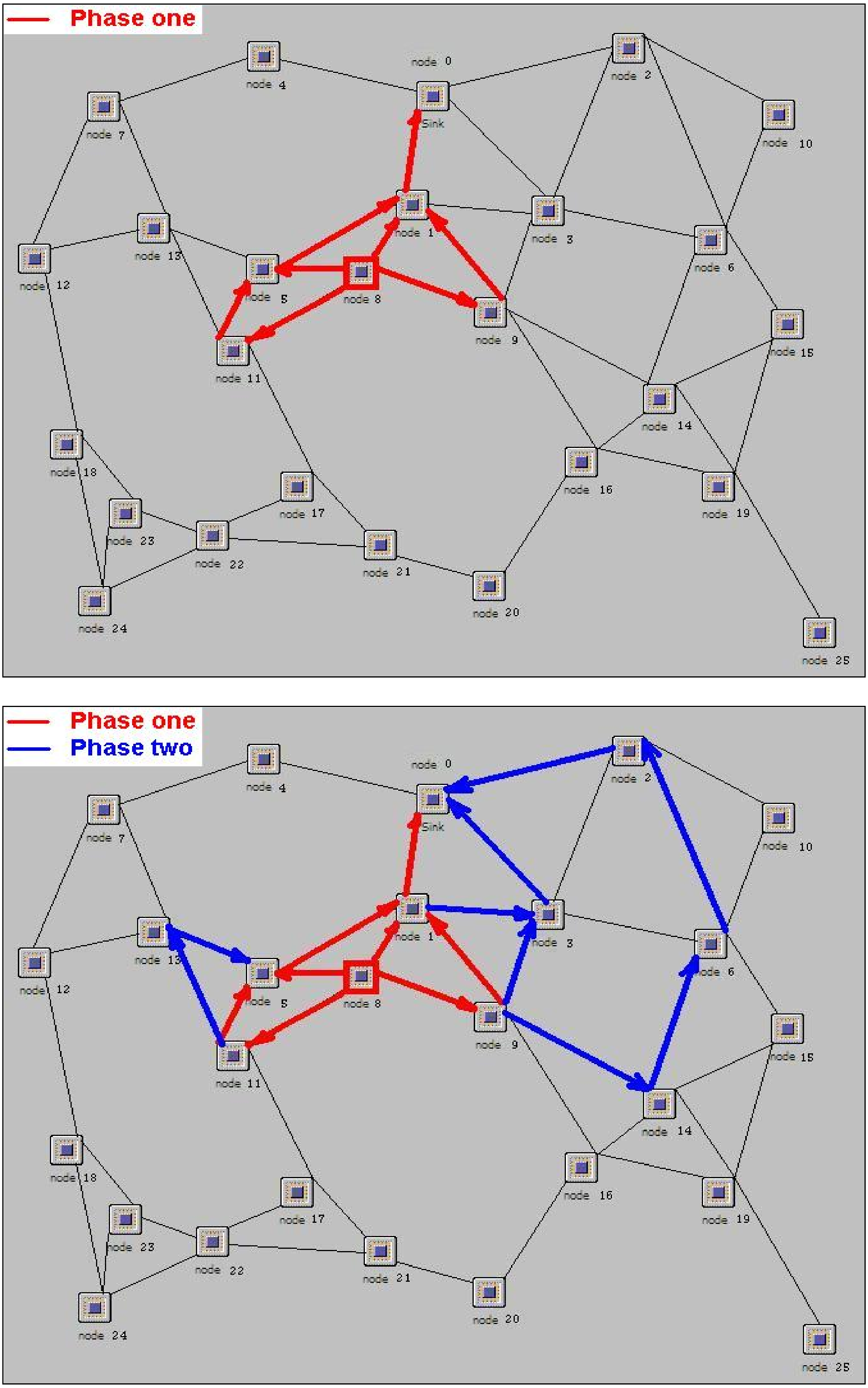


Fig. A.8: Routes discovered by node 8

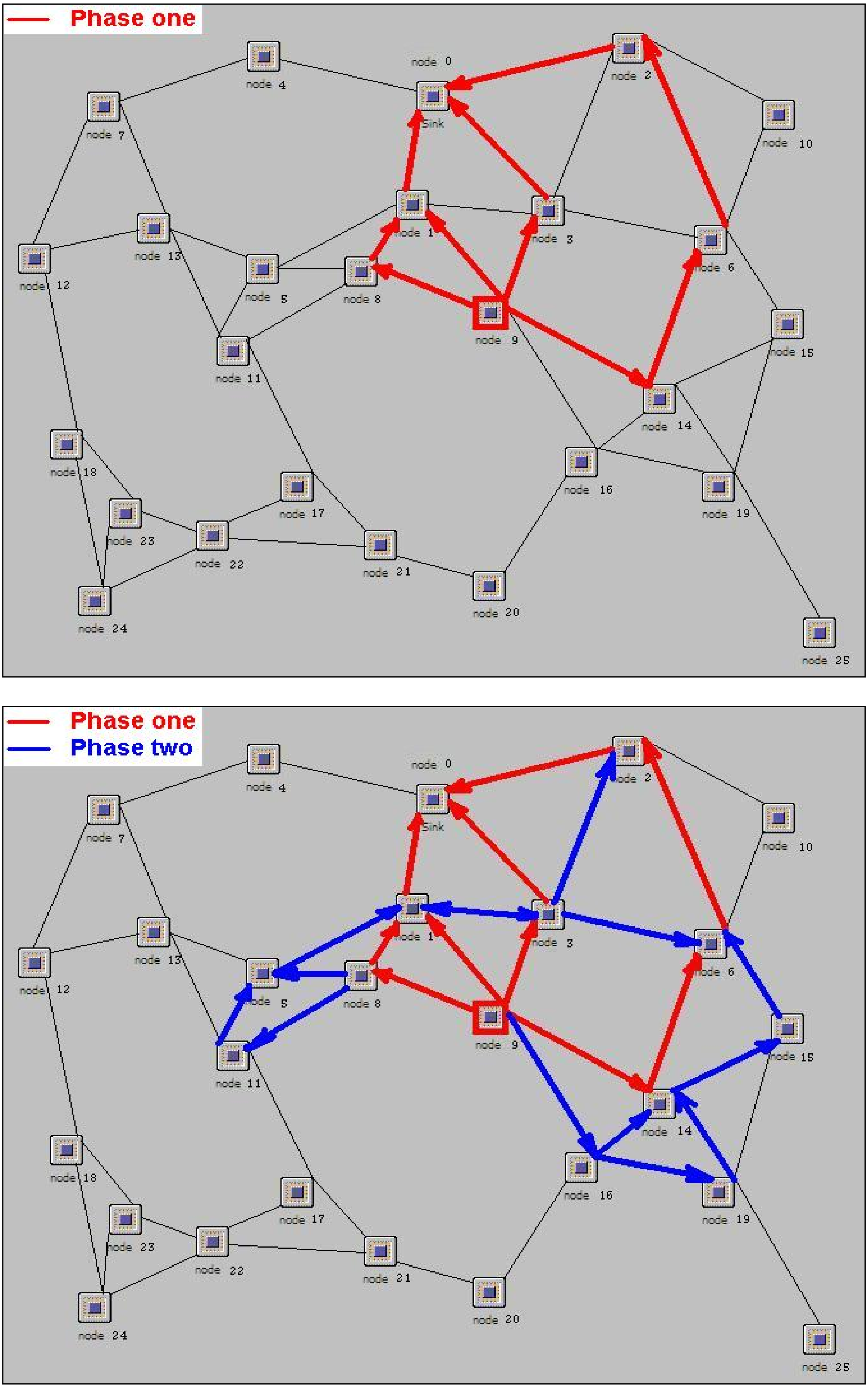


Fig. A.9: Routes discovered by node 9

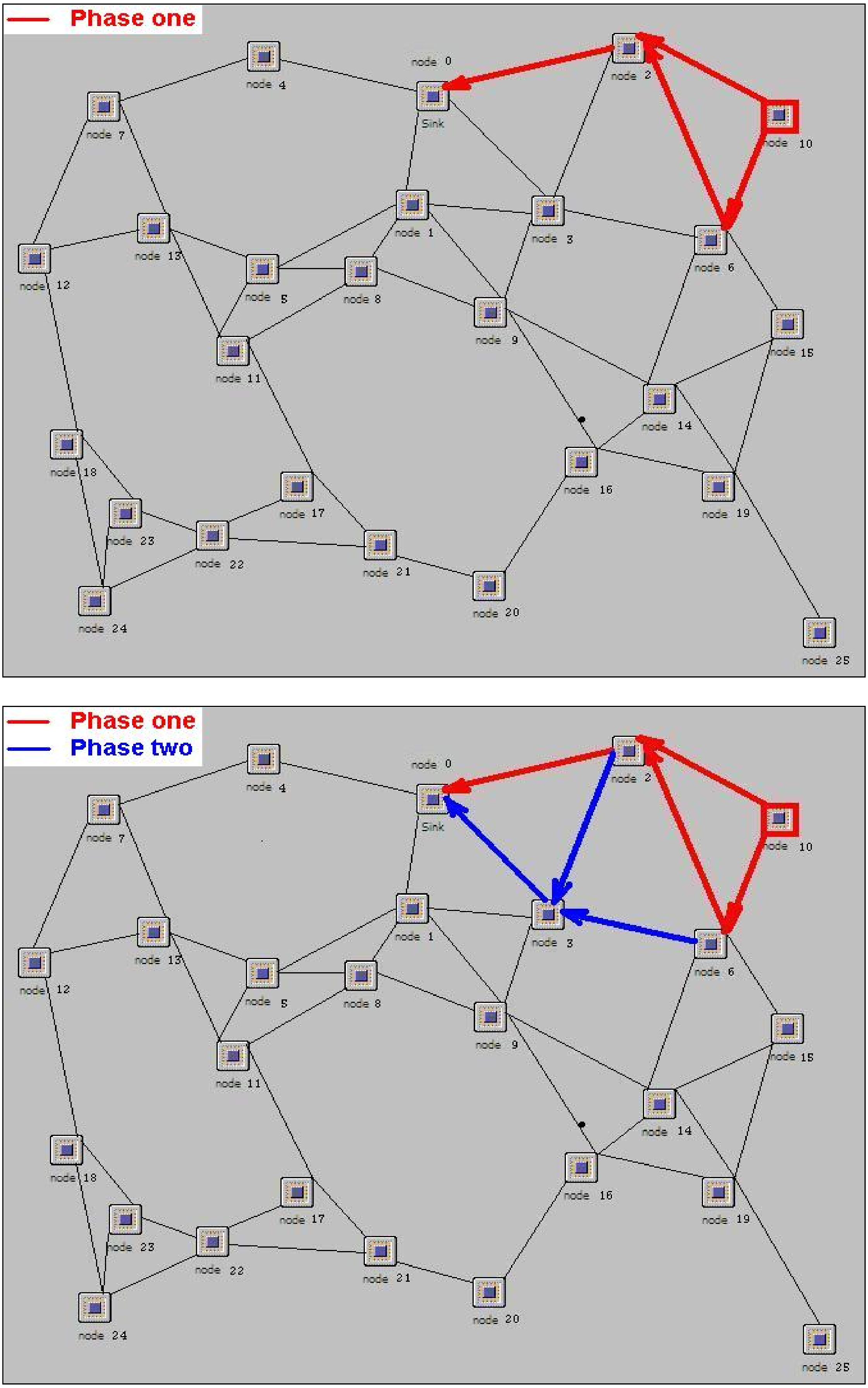


Fig. A.10: Routes discovered by node 10

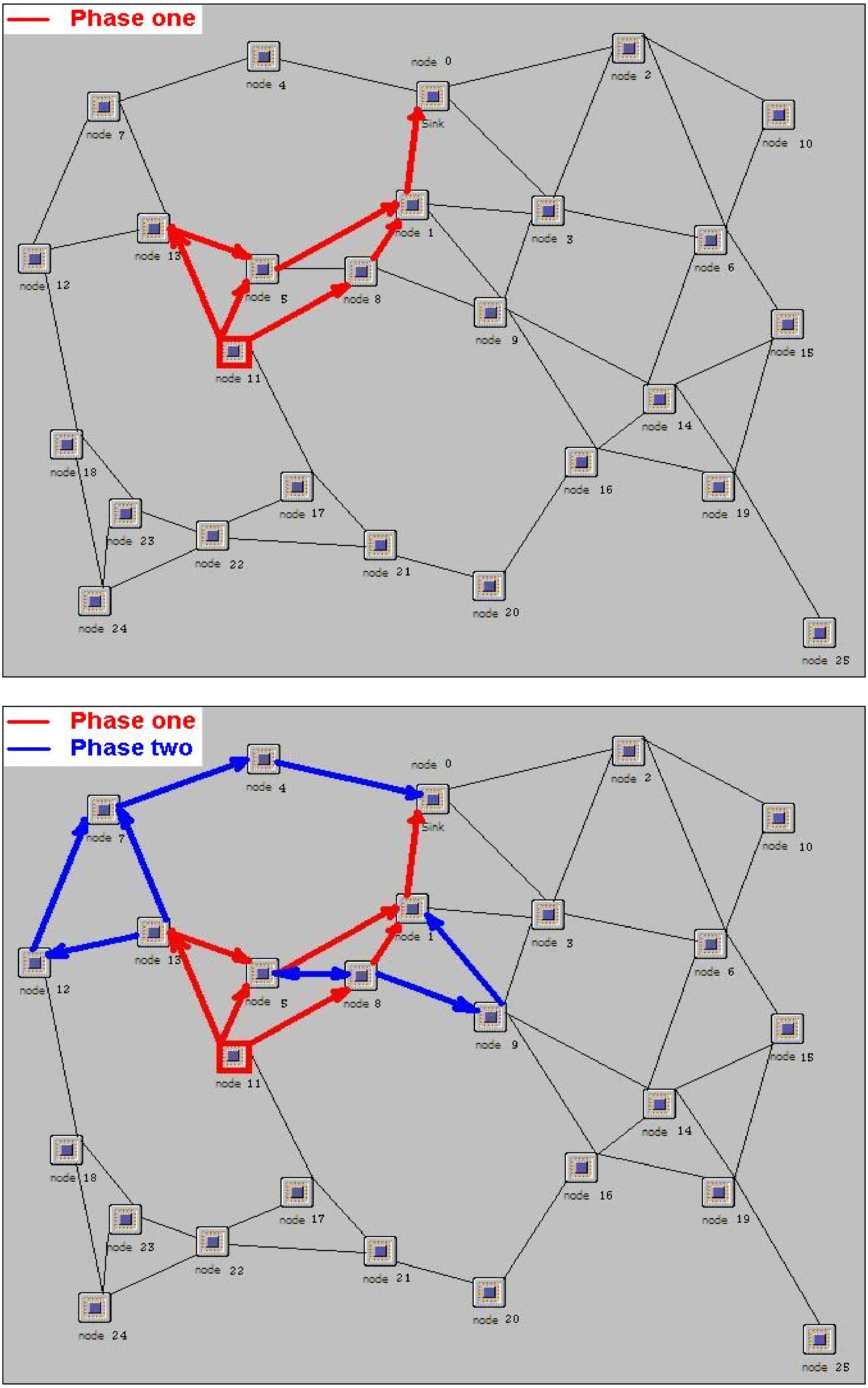


Fig. A.11: Routes discovered by node 11

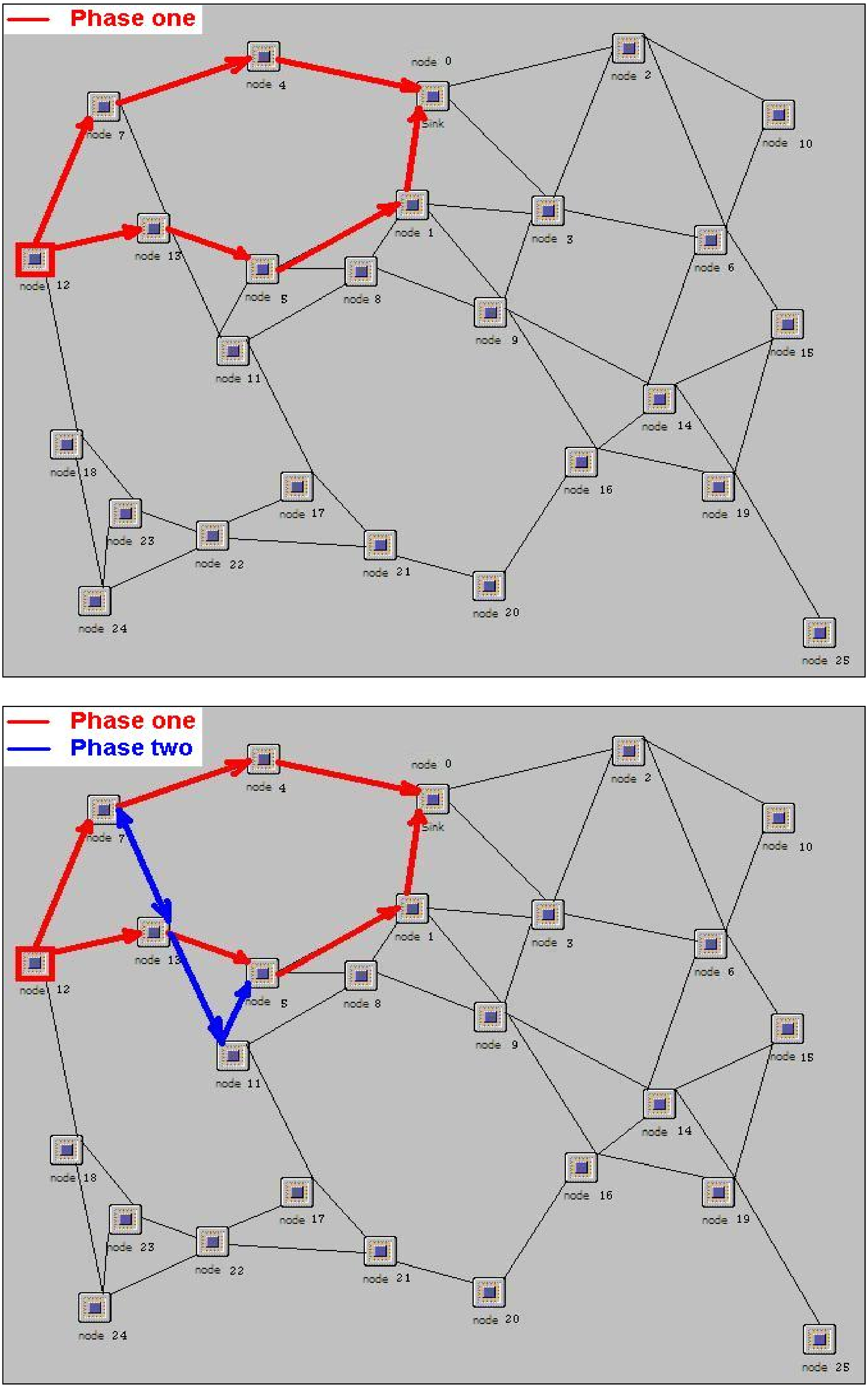


Fig. A.12: Routes discovered by node 12

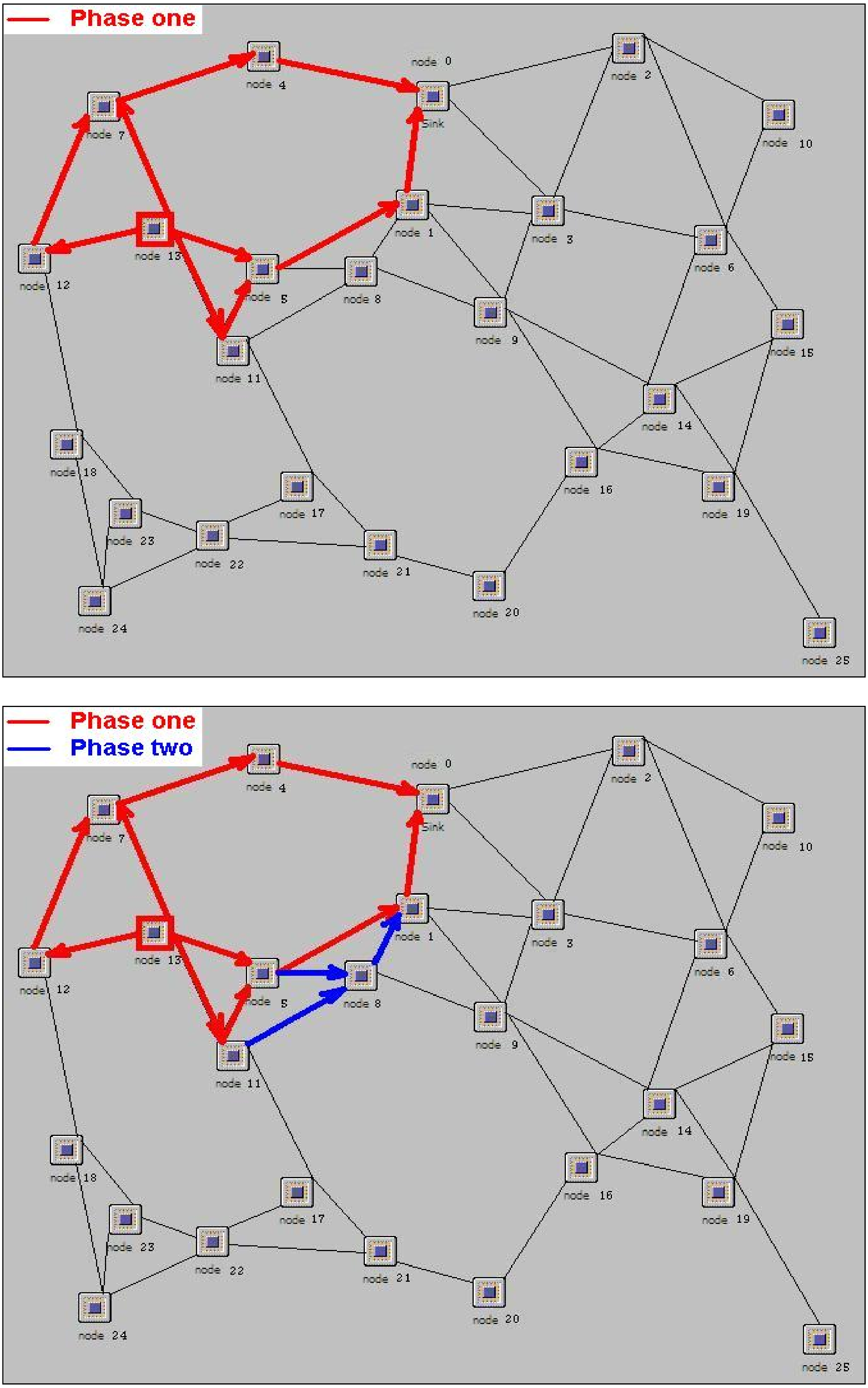


Fig. A.13: Routes discovered by node 13

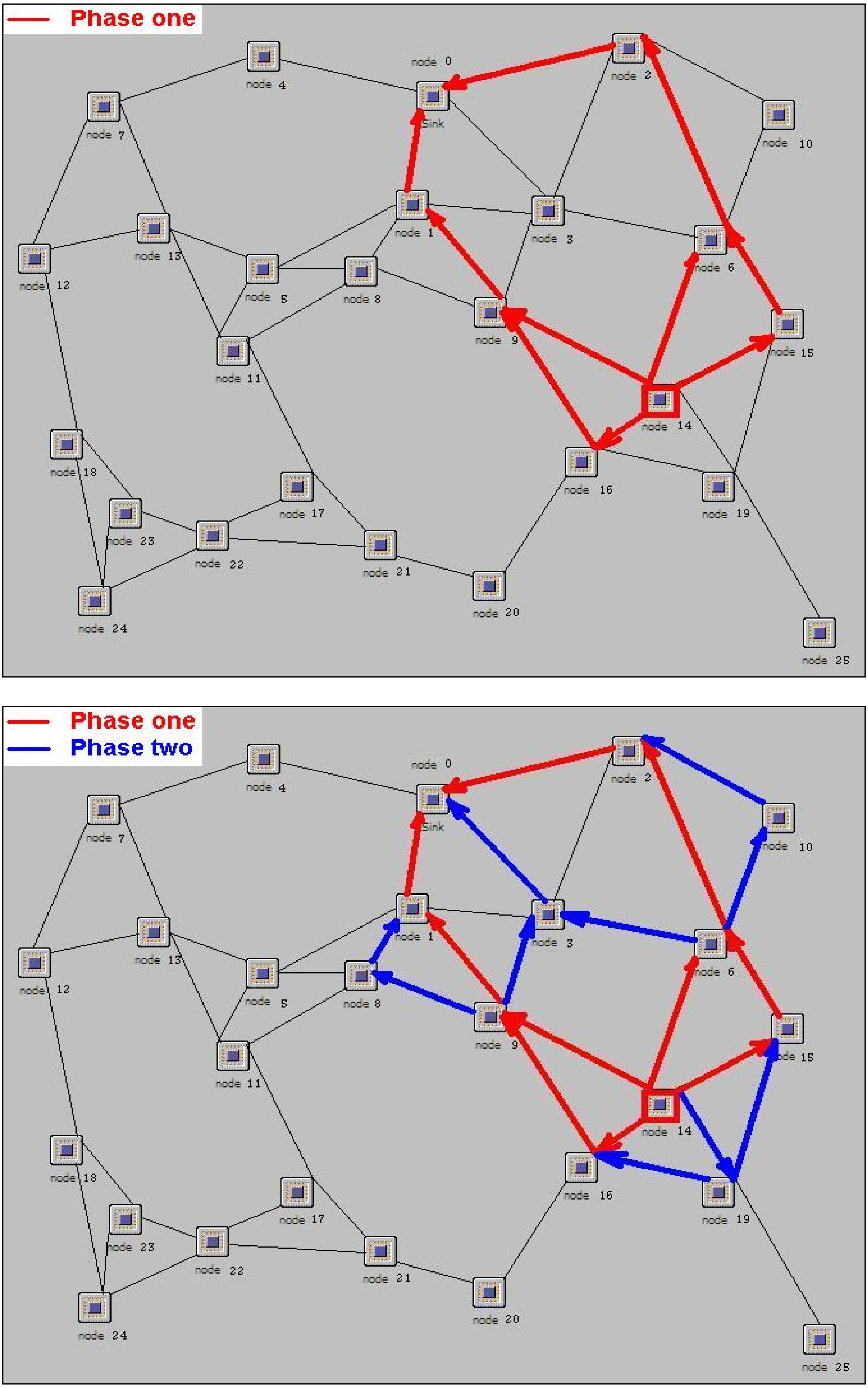


Fig. A.14: Routes discovered by node 14

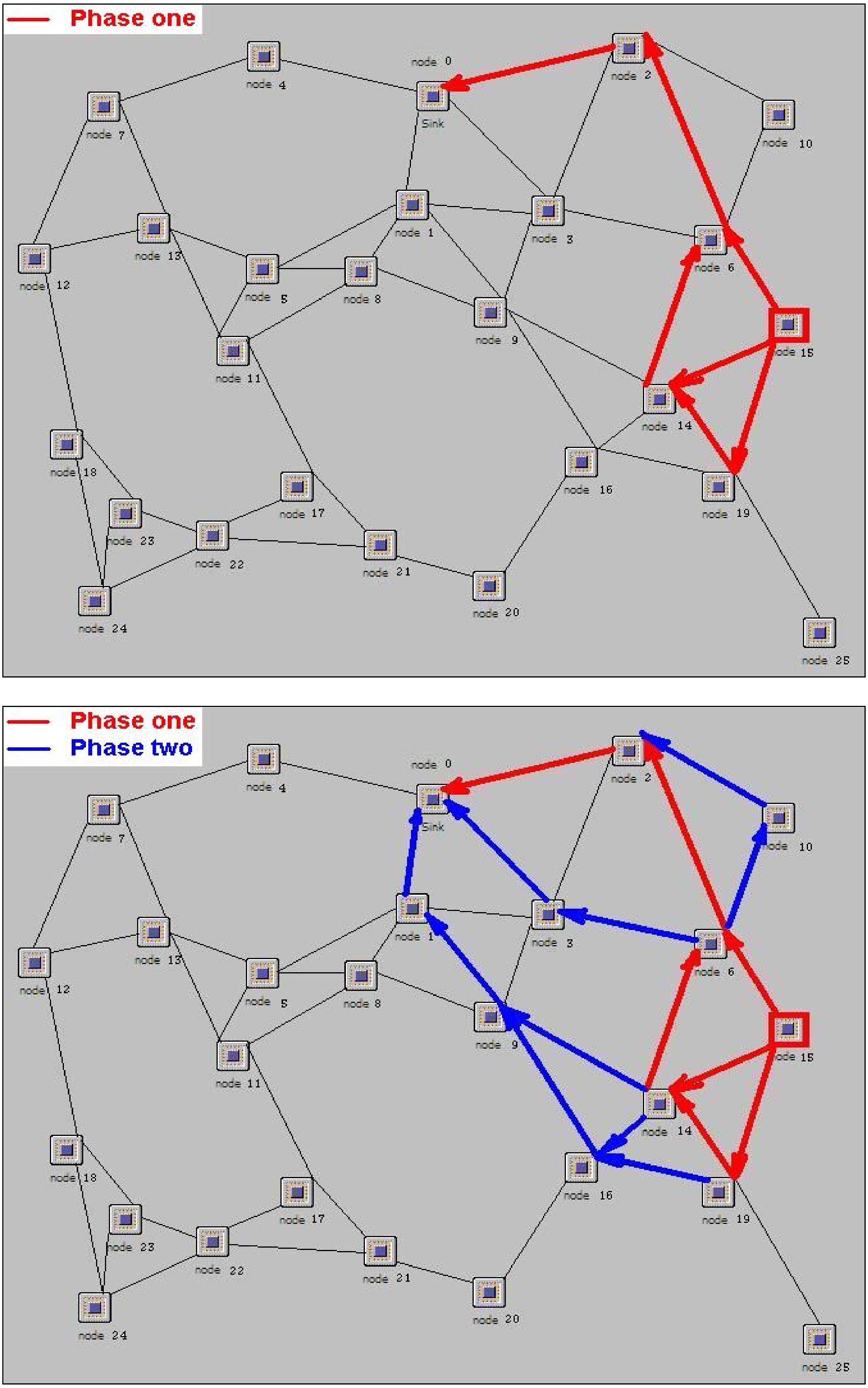
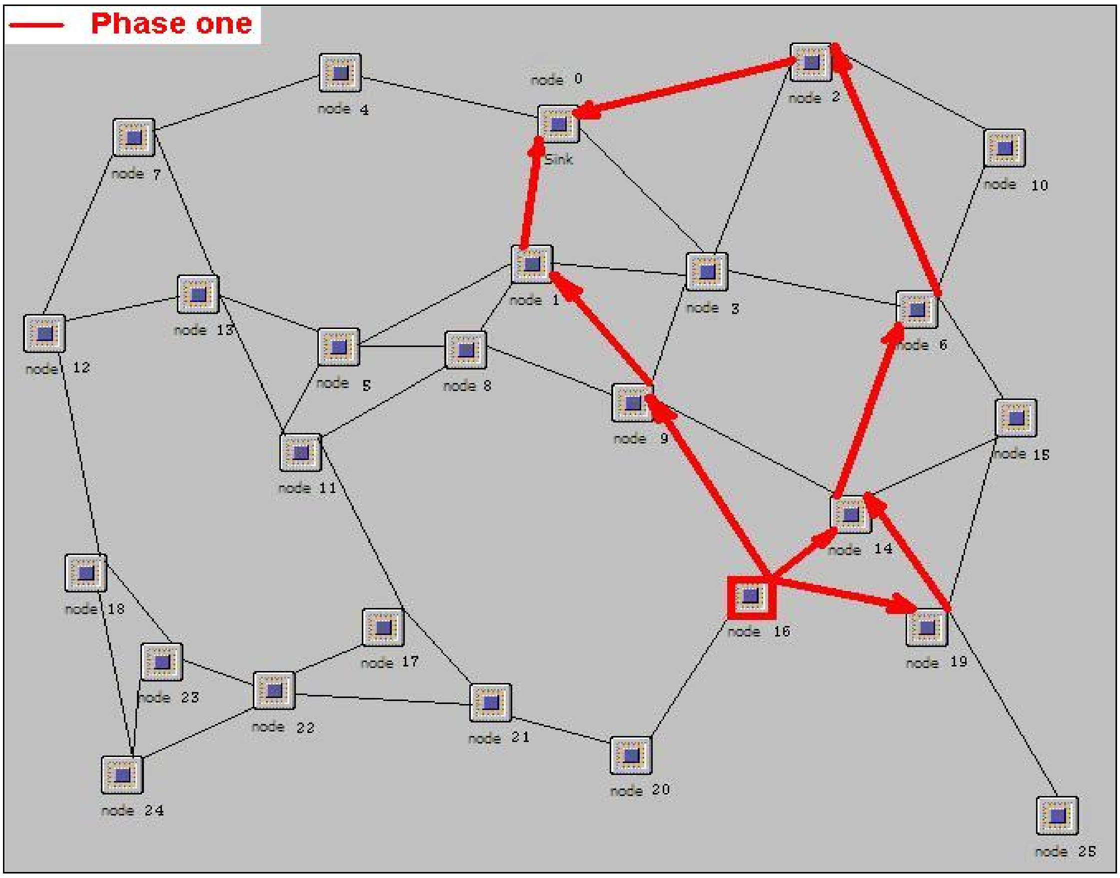


Fig. A.15: Routes discovered by node 15



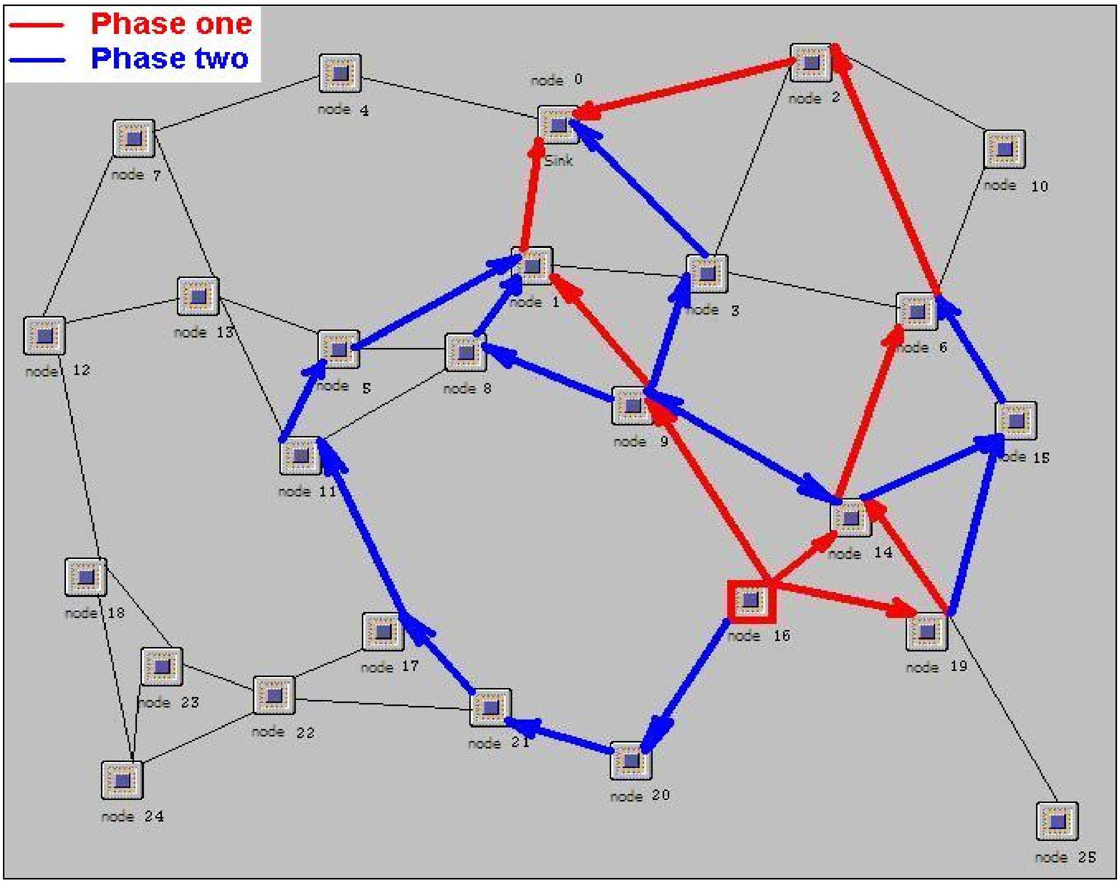
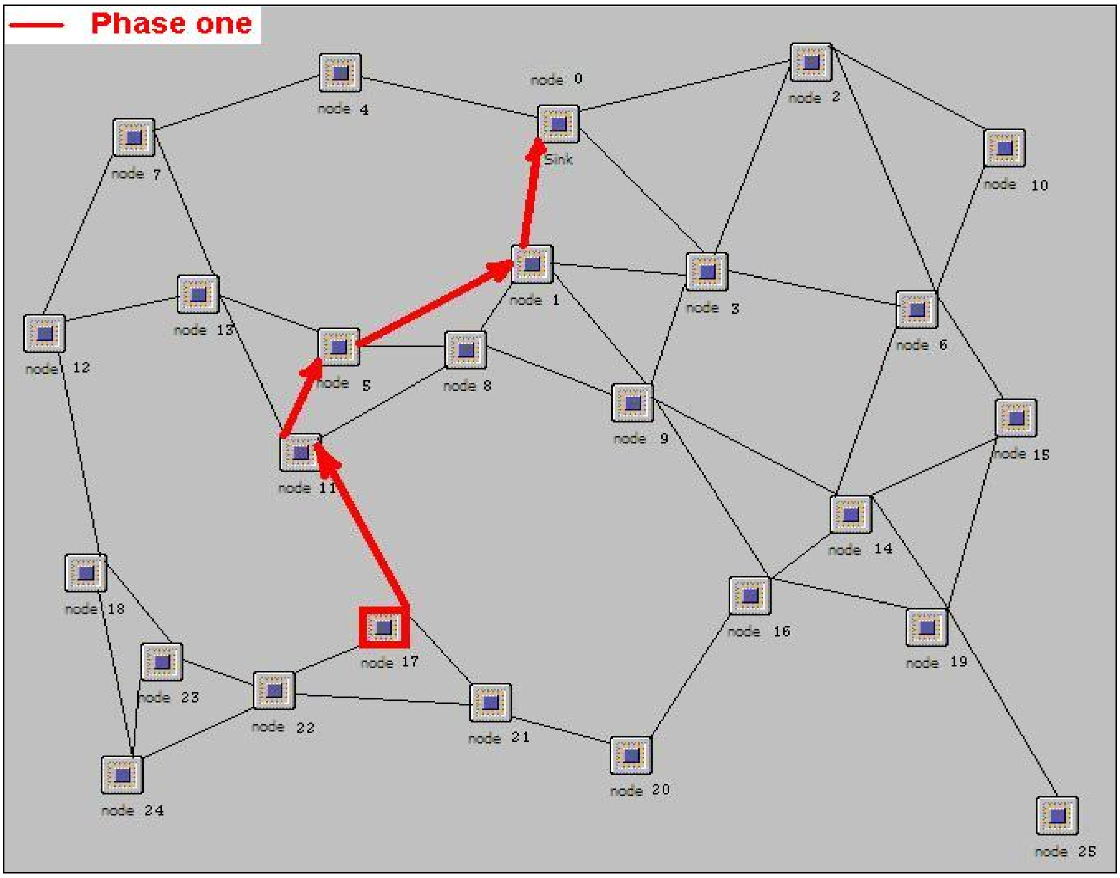


Fig. A.16: Routes discovered by node 16



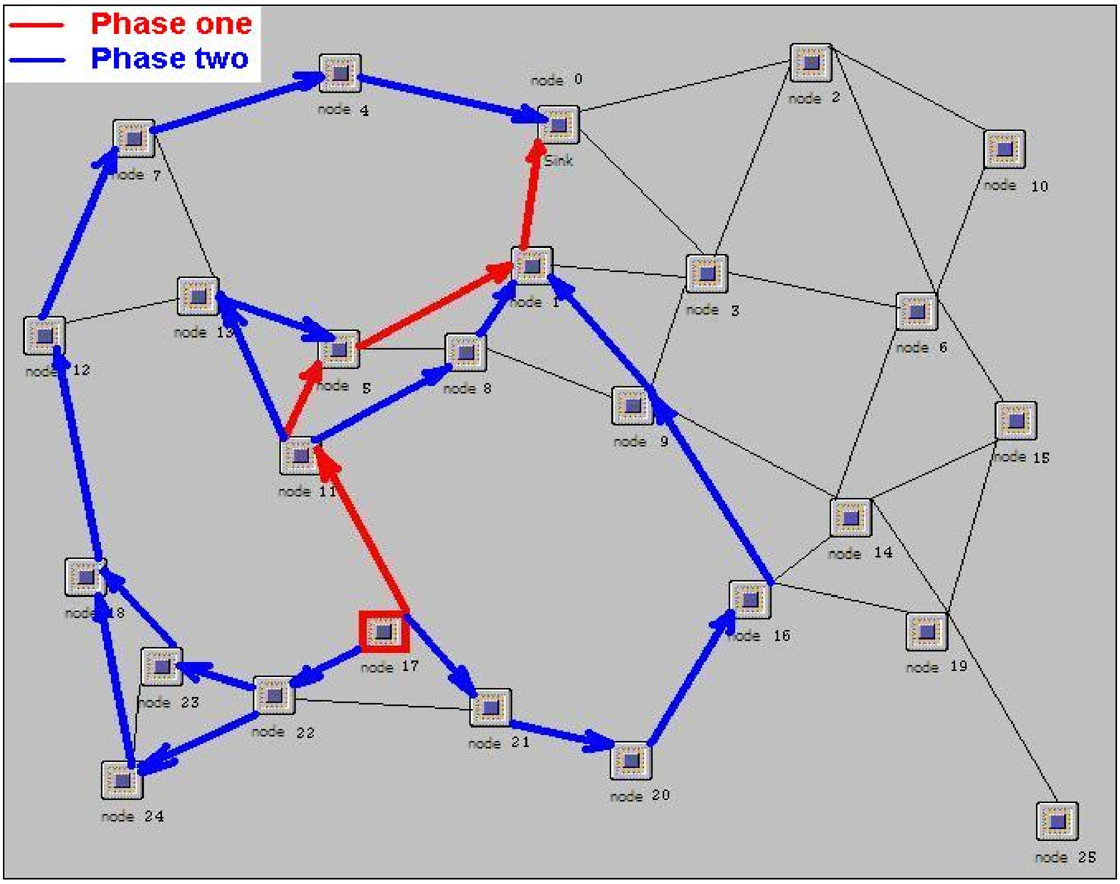


Fig. A.17: Routes discovered by node 17

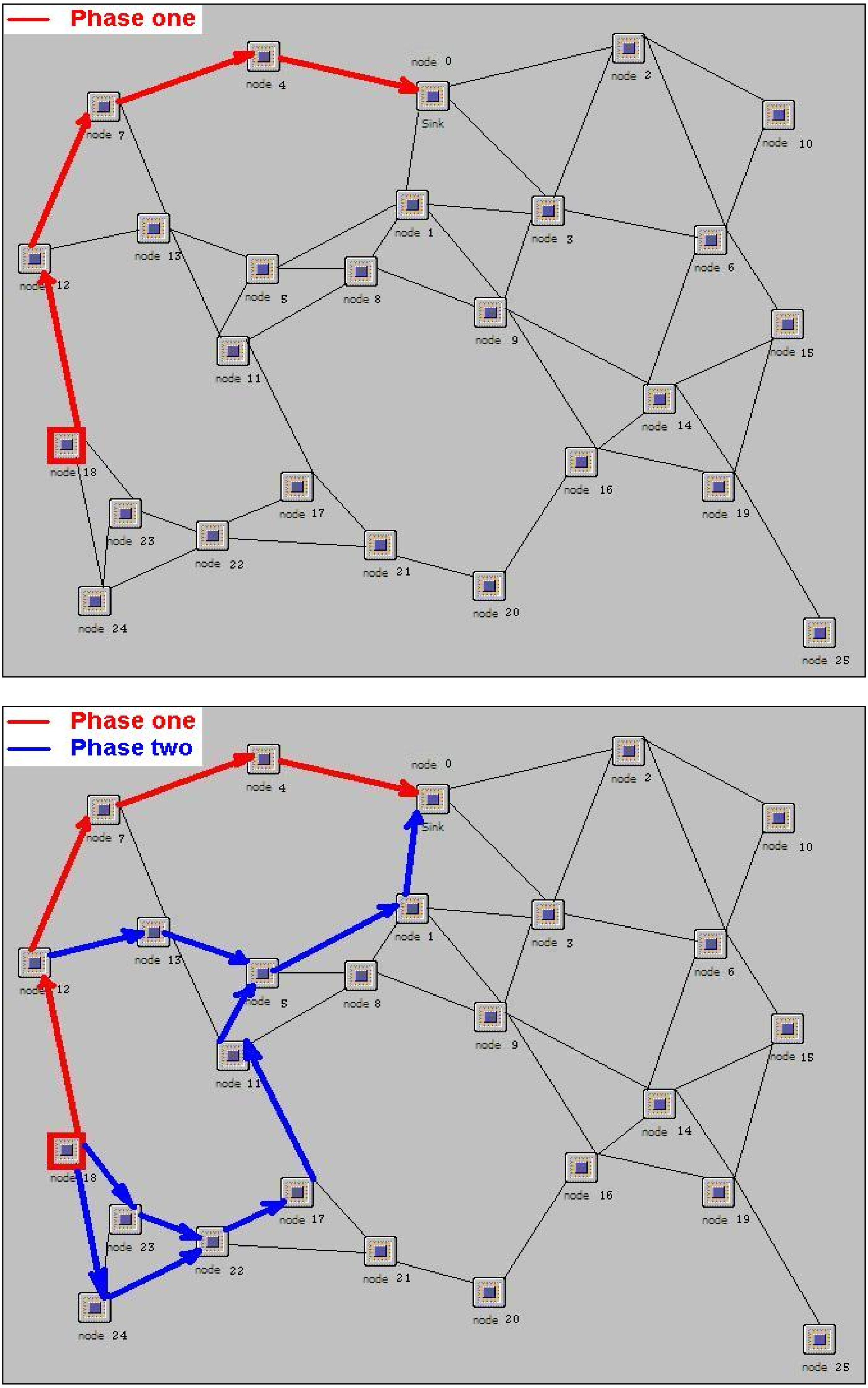
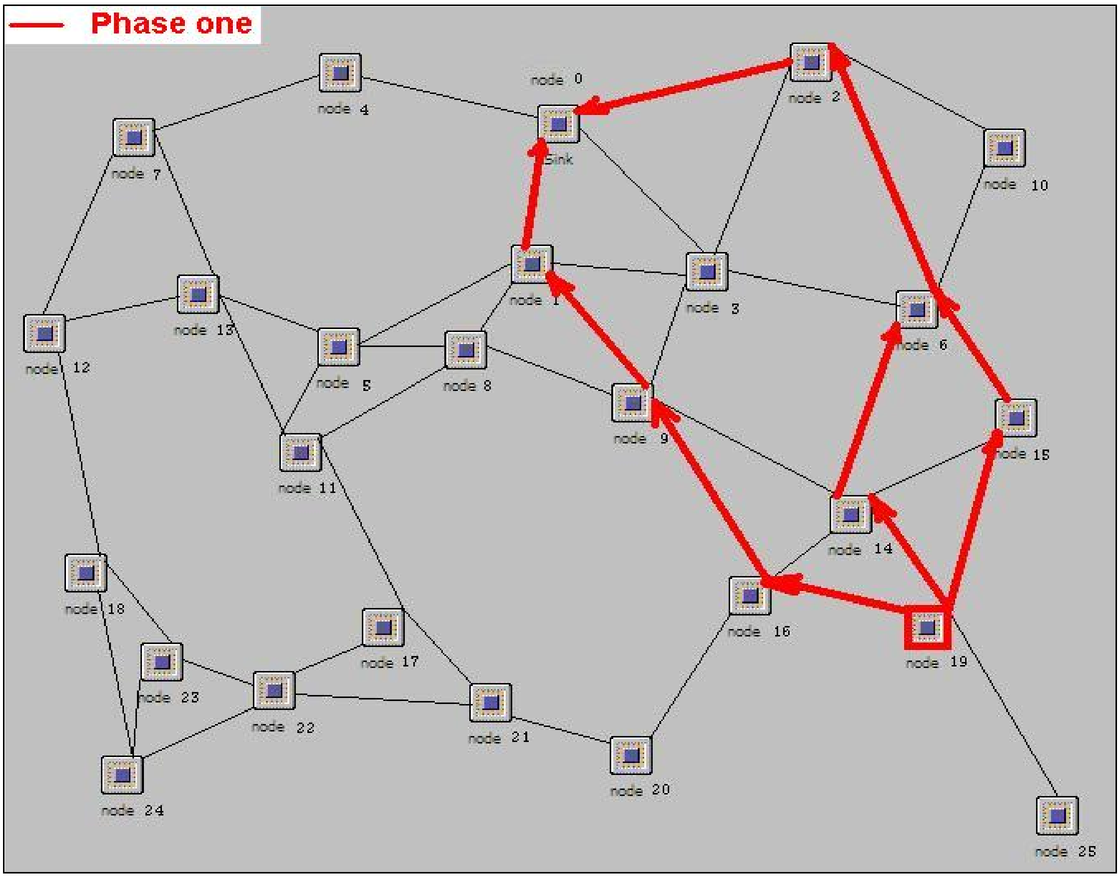


Fig. A.18: Routes discovered by node 18



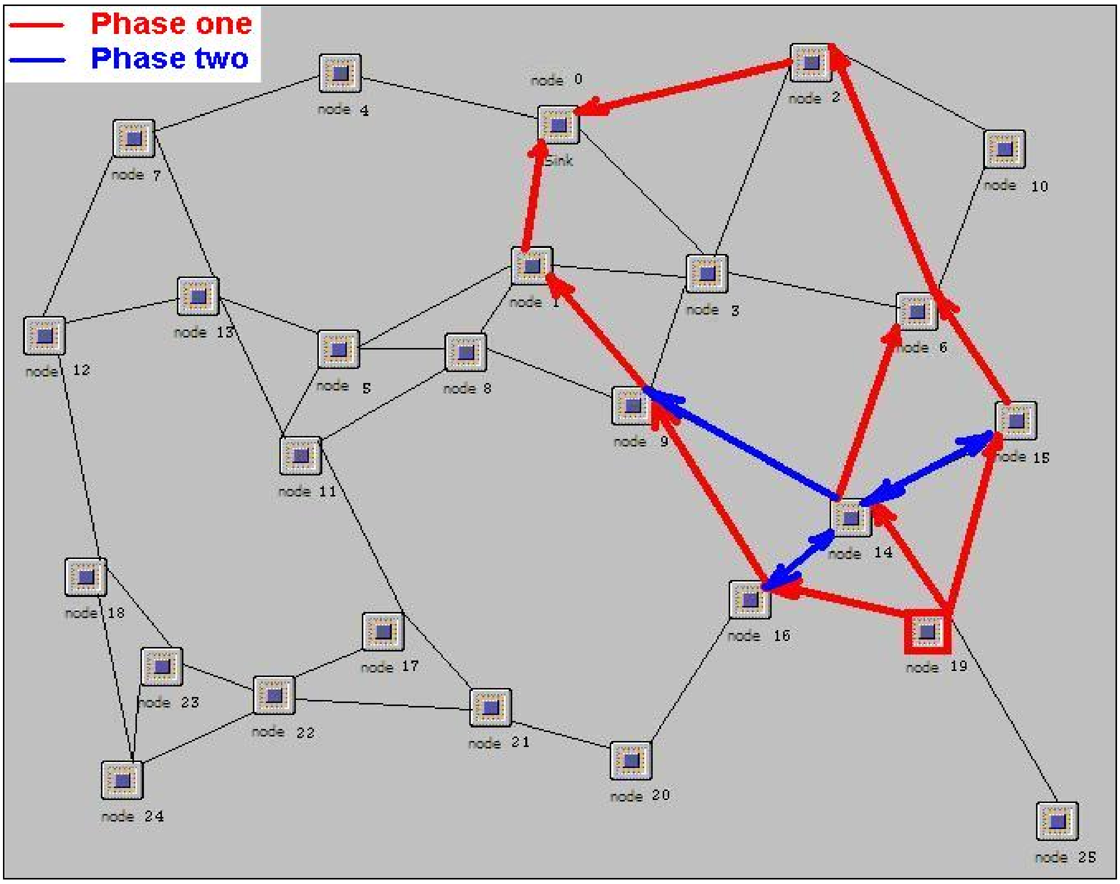


Fig. A.19: Routes discovered by node 19

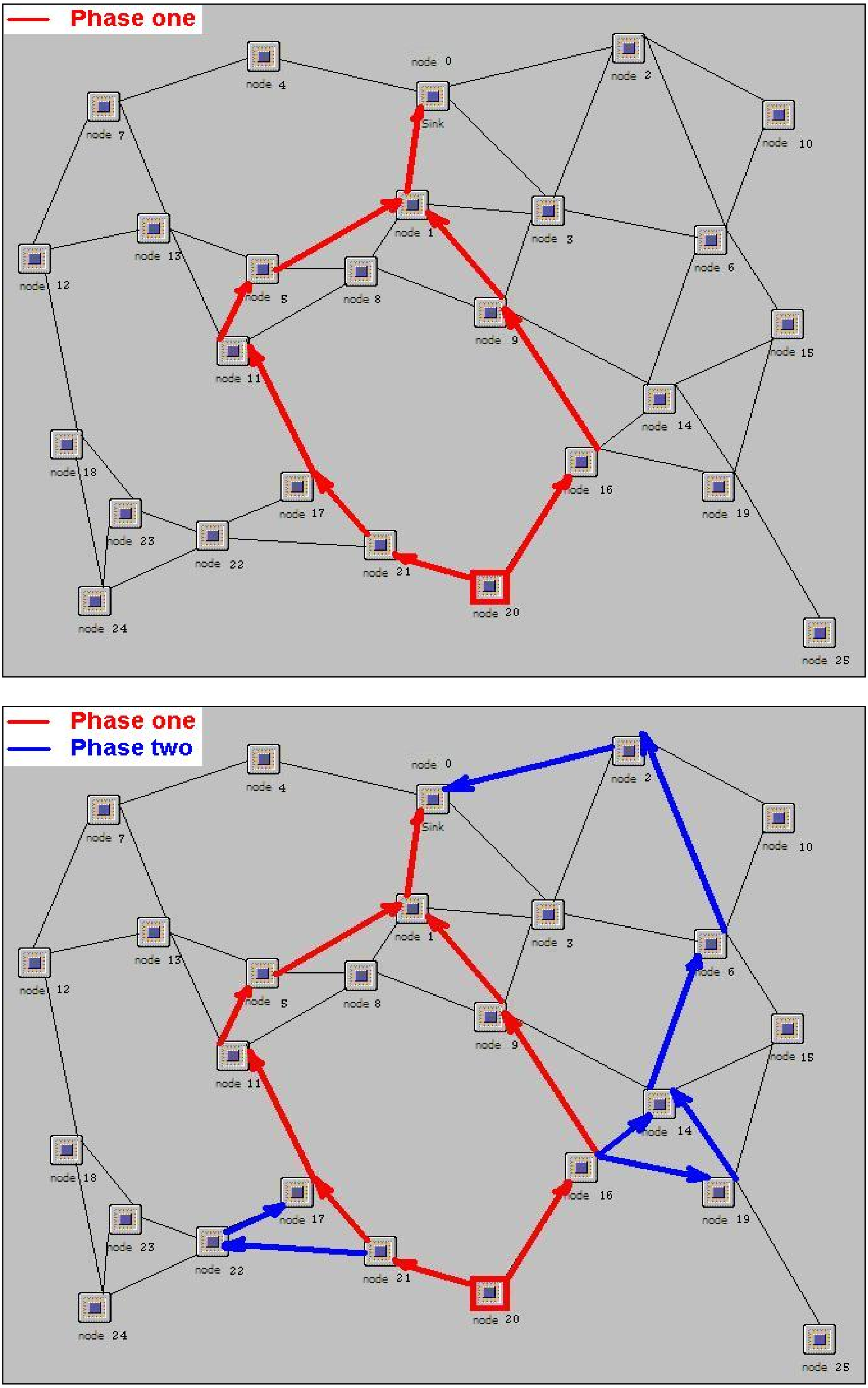


Fig. A.20: Routes discovered by node 20

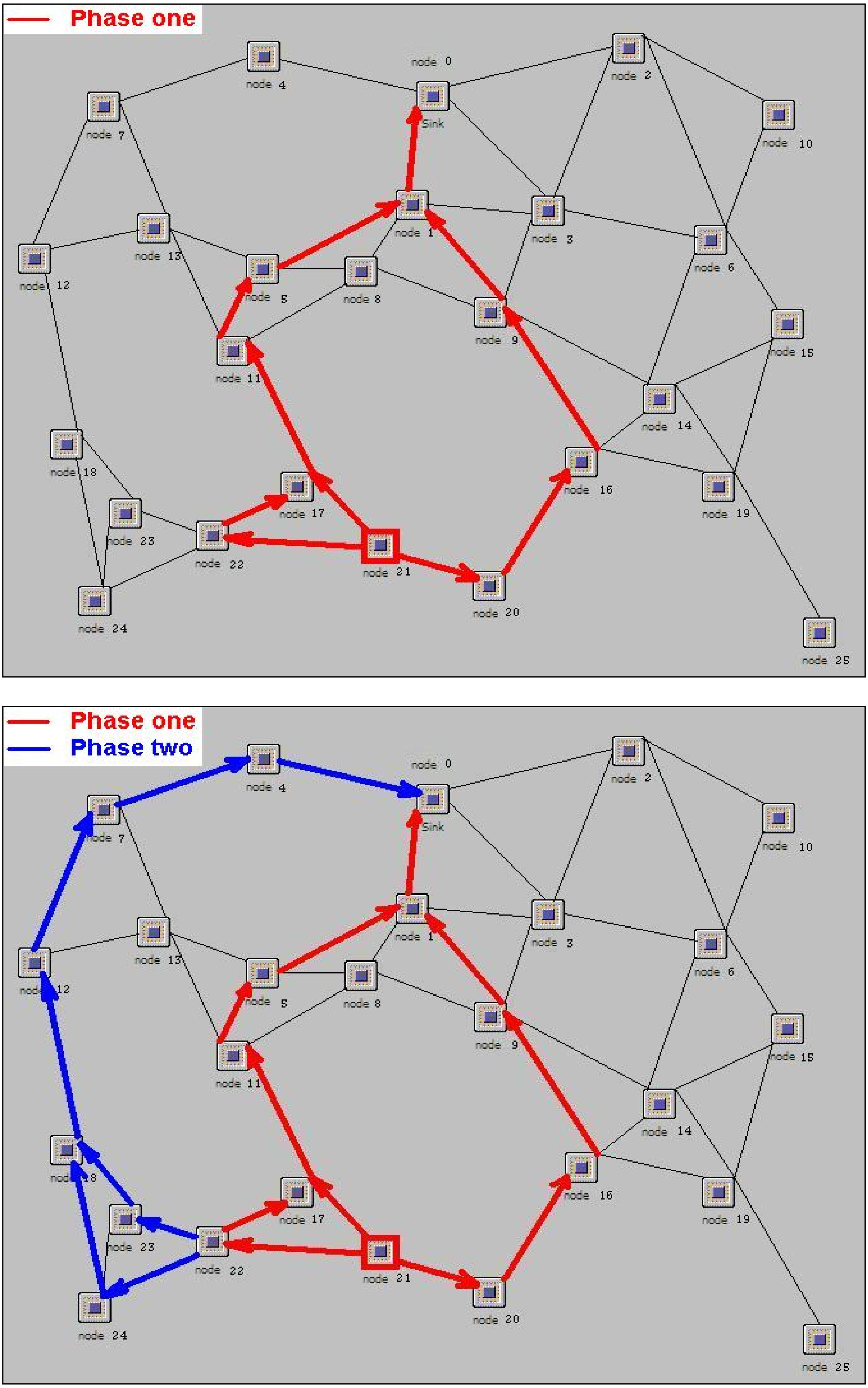
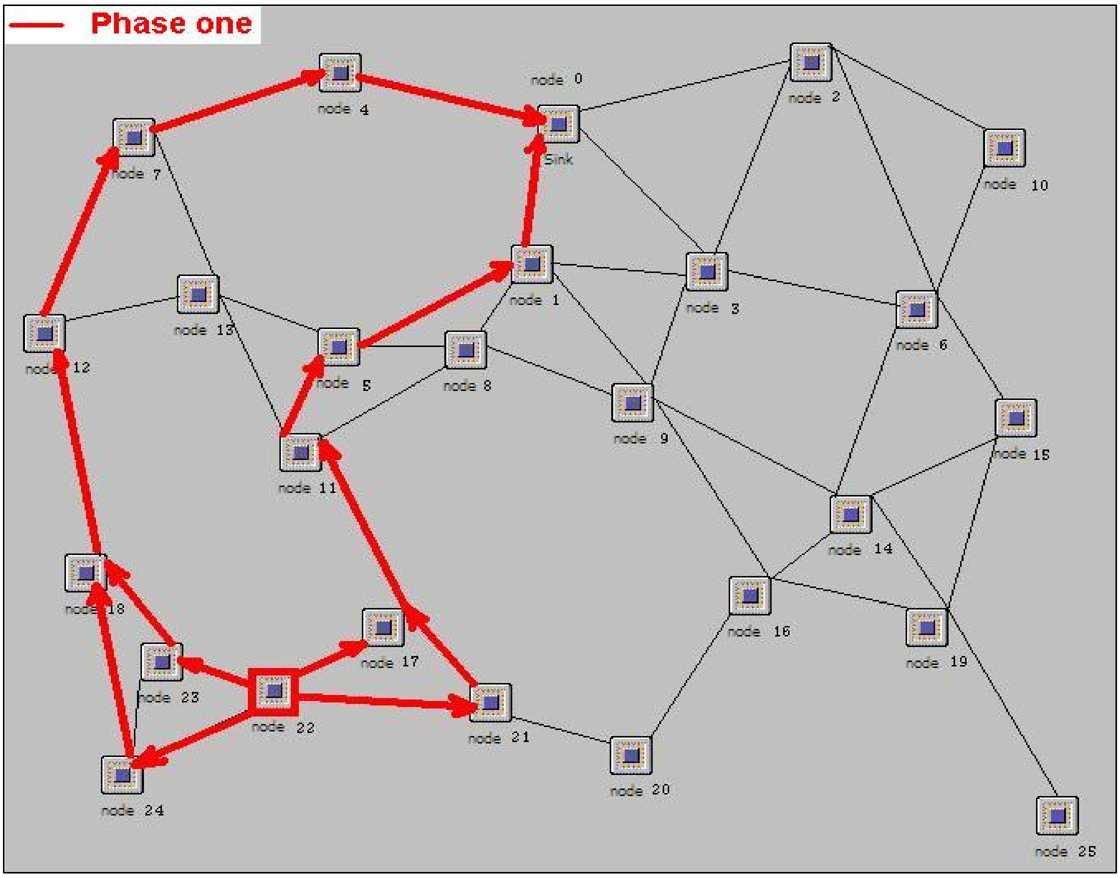


Fig. A.21: Routes discovered by node 21



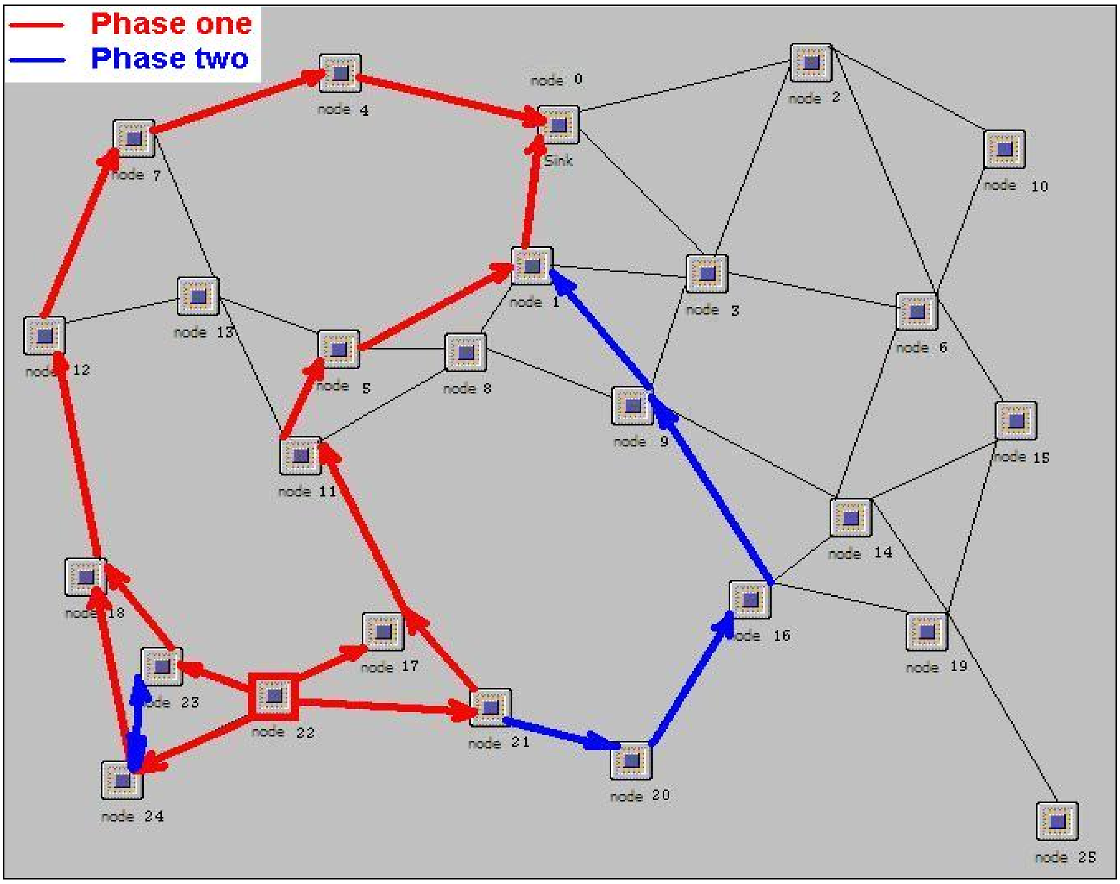


Fig. A.22: Routes discovered by node 22

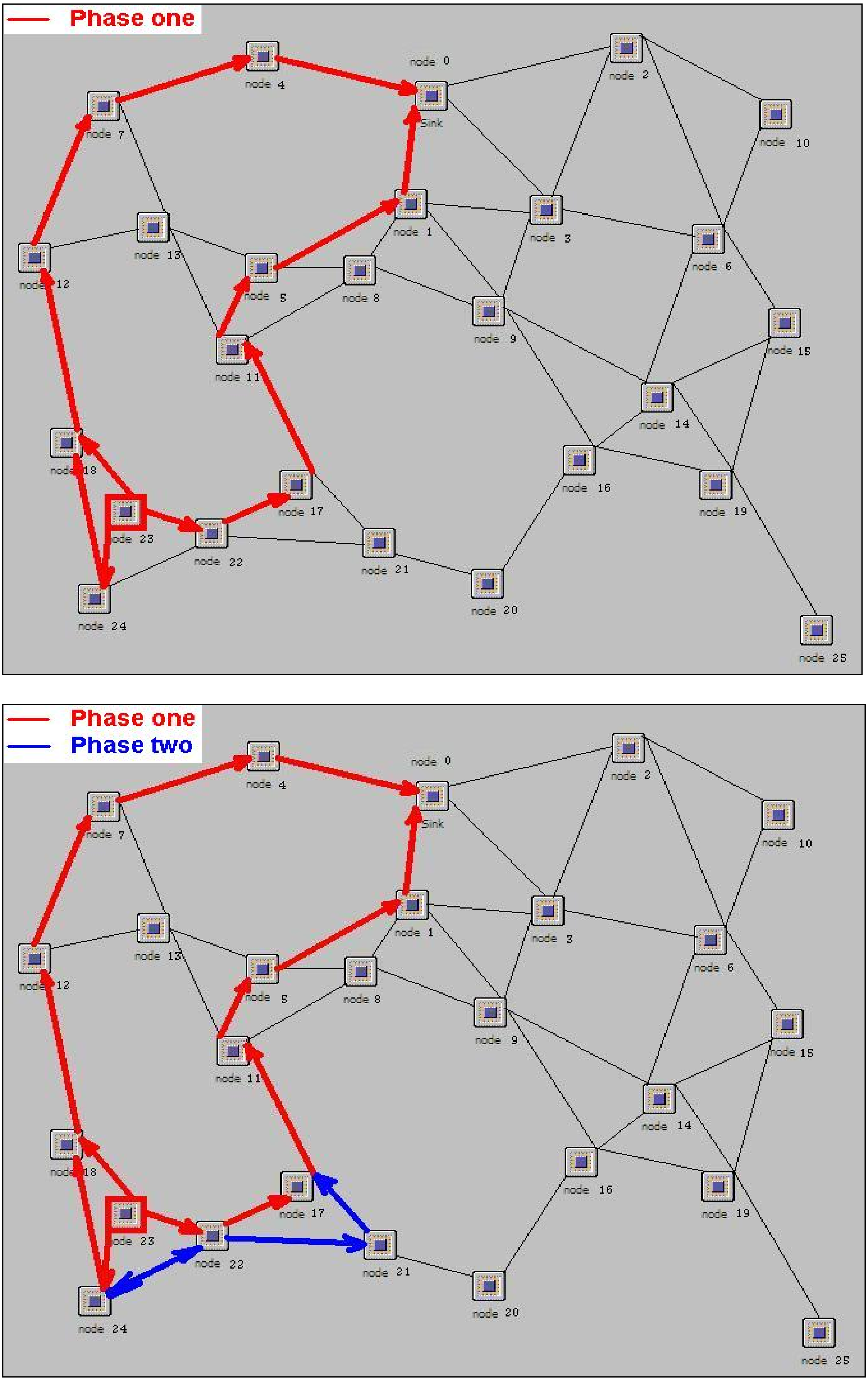


Fig. A.23: Routes discovered by node 23

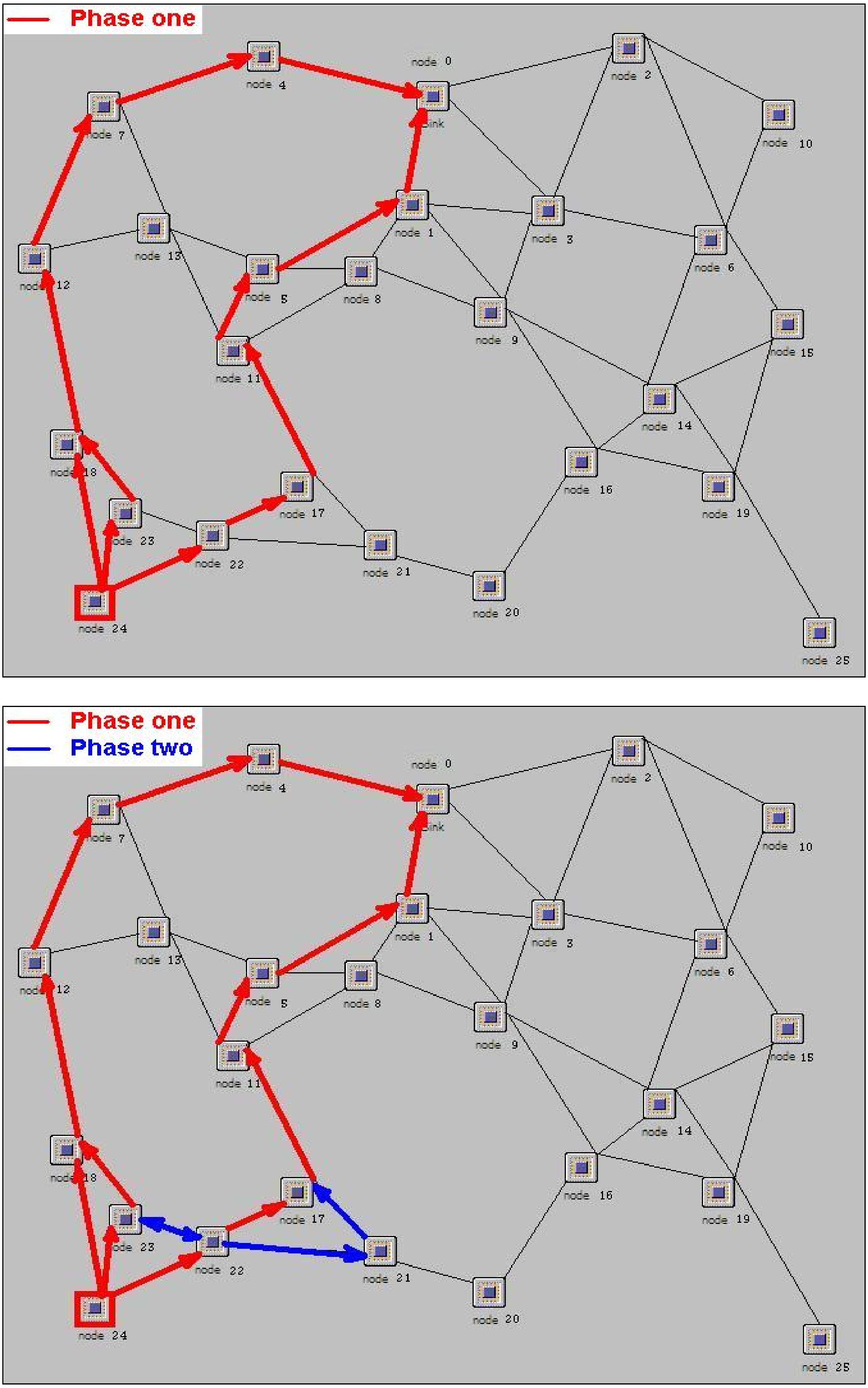


Fig. A.24: Routes discovered by node 24

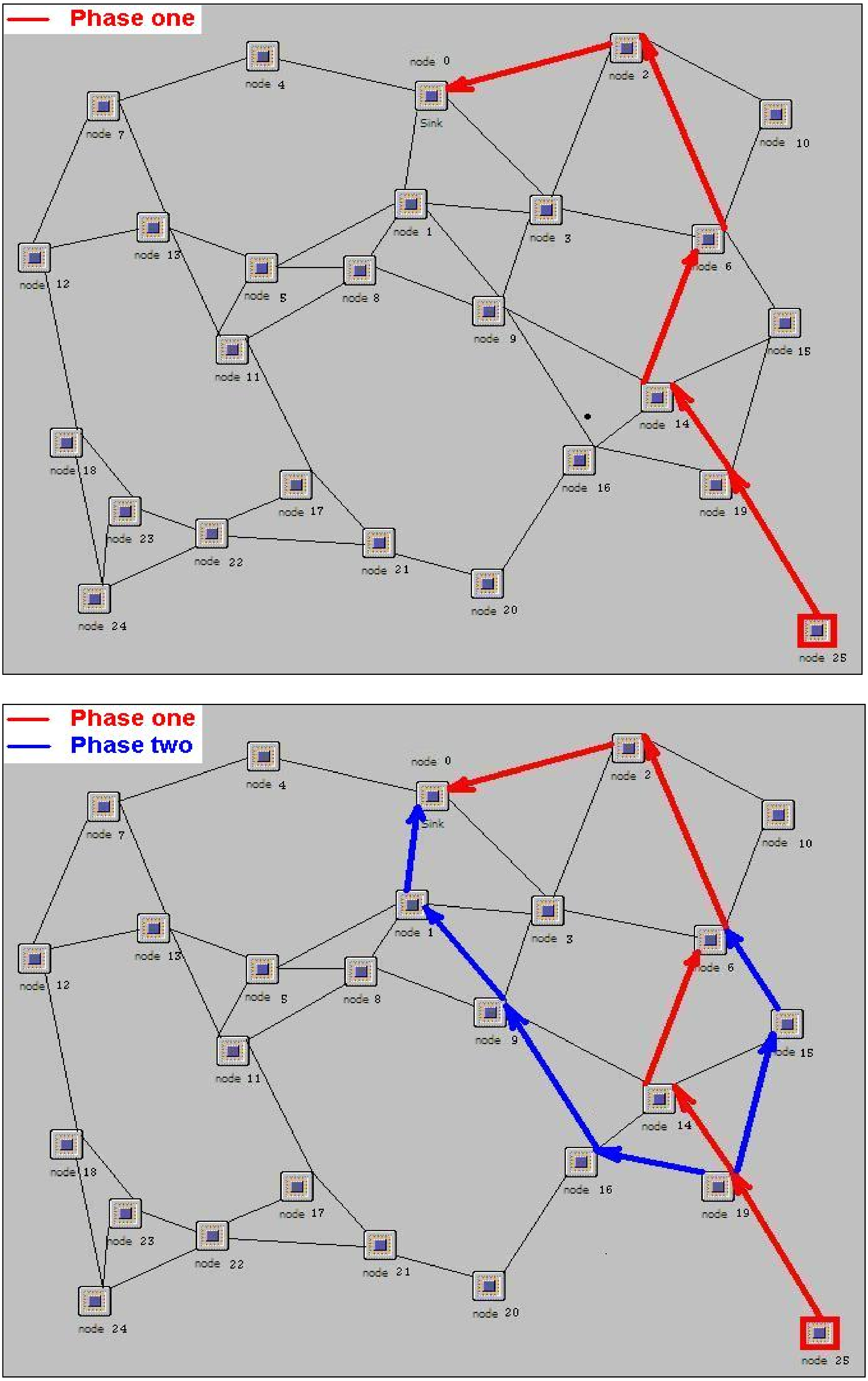


Fig. A.25: Routes discovered by node 25

Appendix B: Network Statistics

The statistics shown below are for the network characteristics when Type-Four Broadcast is used in Phase-One of the Multipath Finding Protocol.

Fig. B.1 shows the number of routes discovered by every node in the network. The nodes are ordered by the number of routes that each node discover. Fig. B.2 shows the number of routes discovered by every node in the network ordered by their node ID.

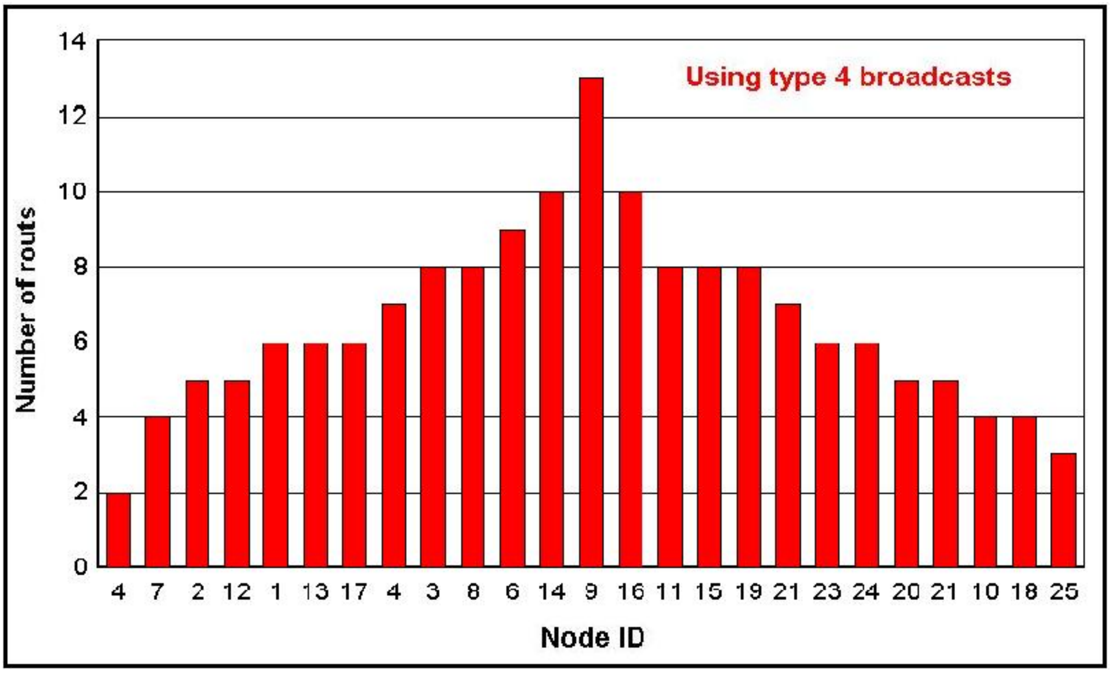


Fig. B.1: Number of routes discovered by every node

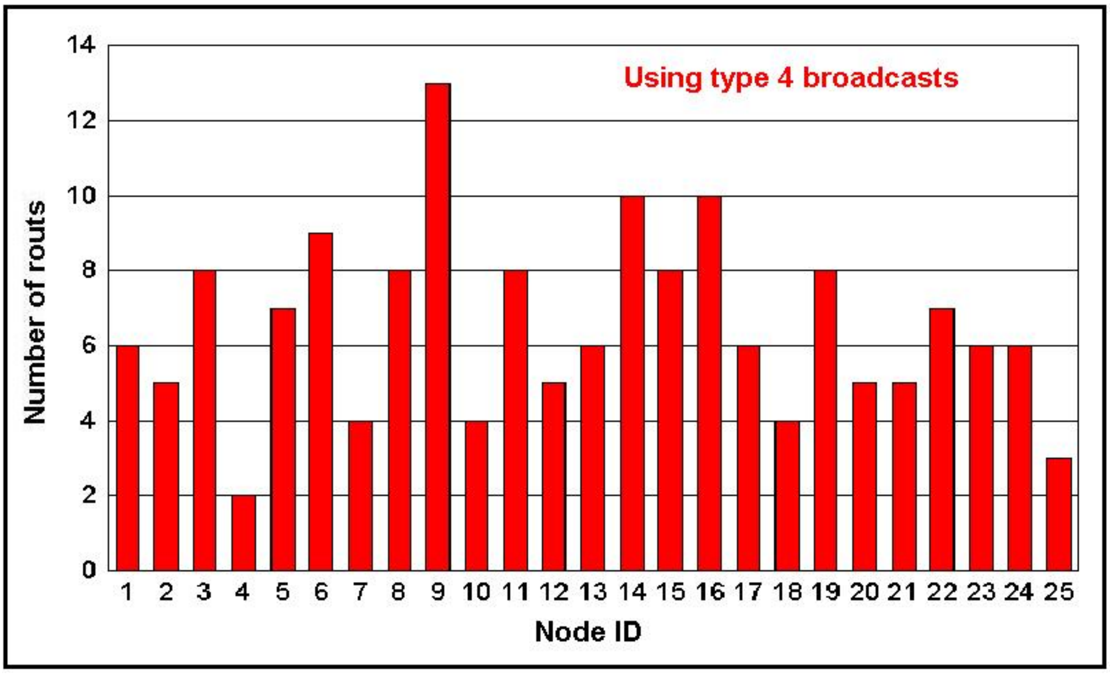


Fig. B.2: Number of routes discovered by every node

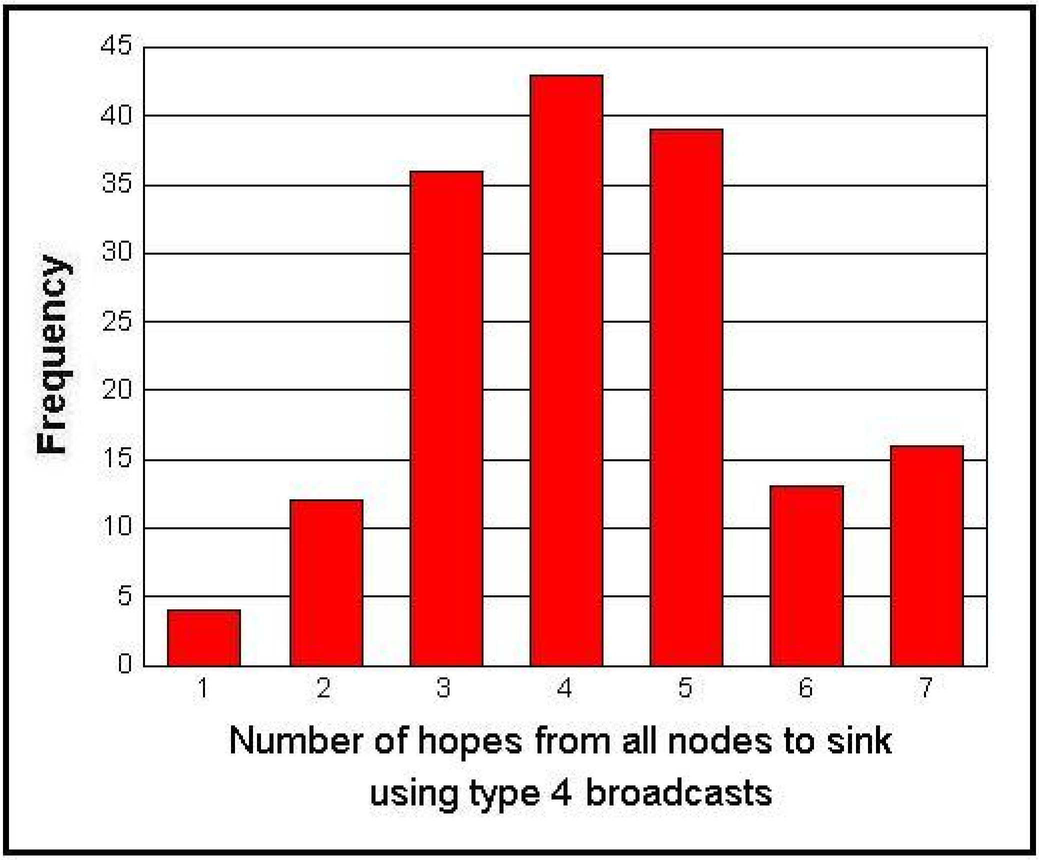


Fig. B.3: Number of hops per route for all network routes

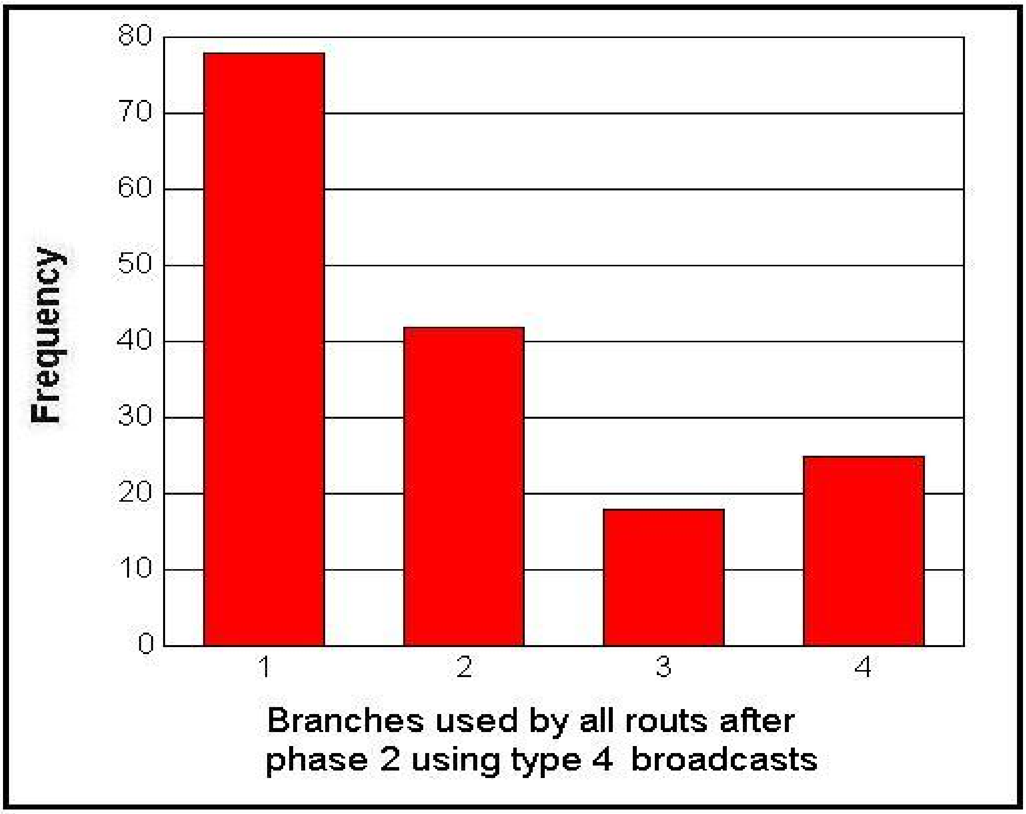


Fig. B.4: Number of network routes going through each of the network branches

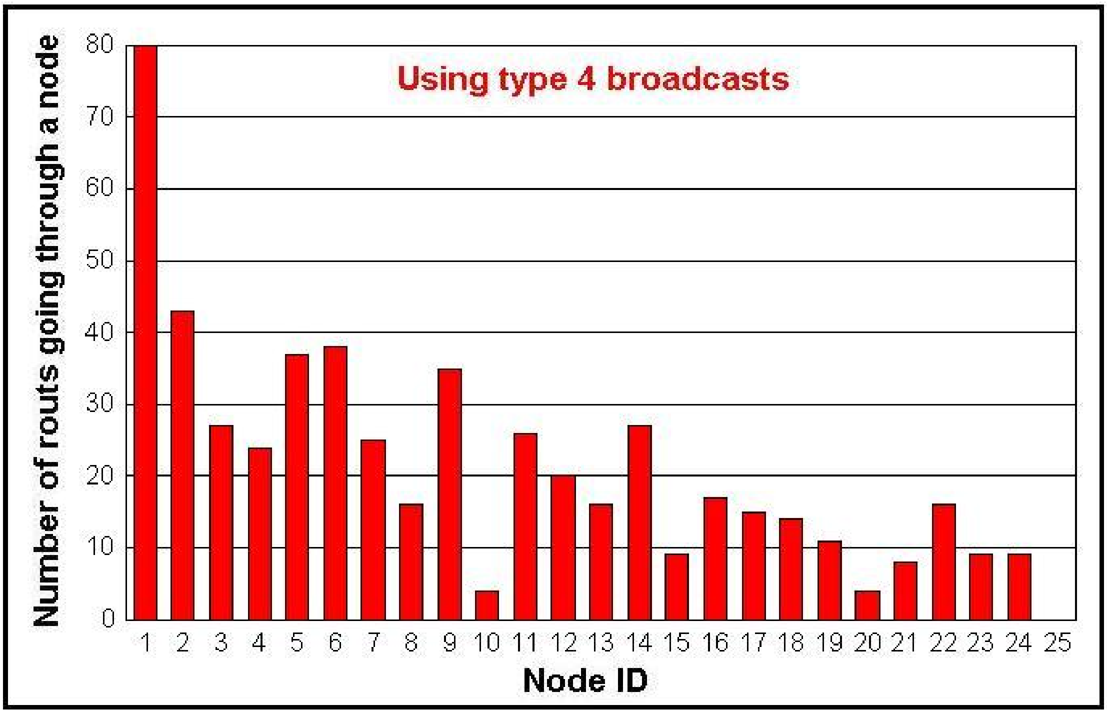


Fig. B.5: Number of routes going through each node

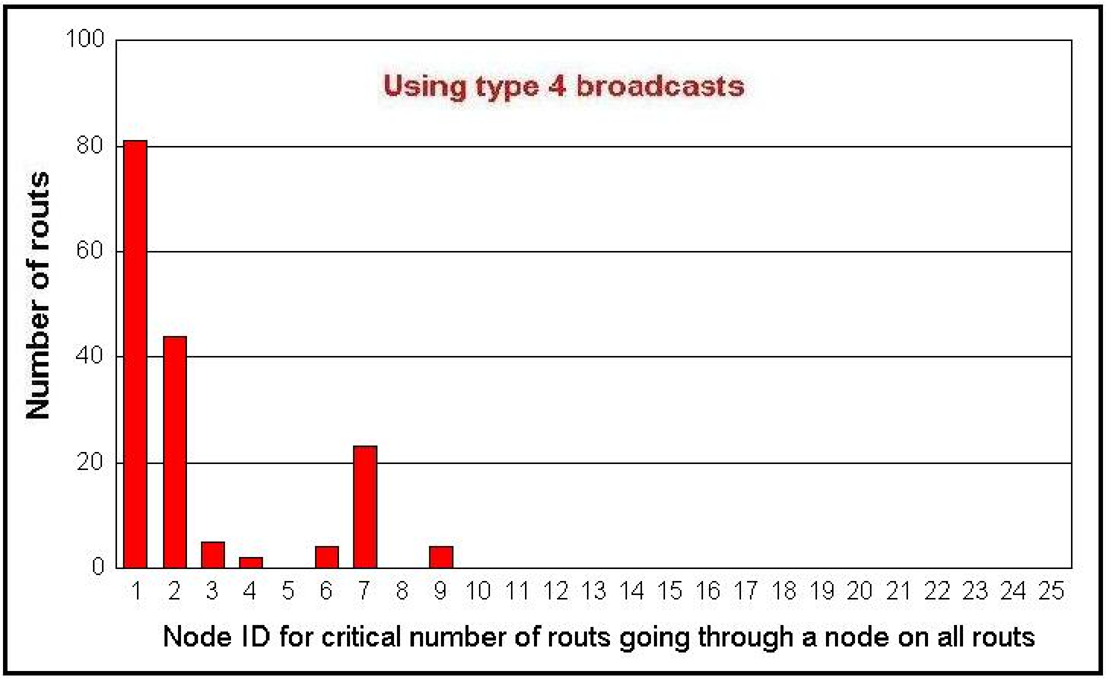


Fig. B.6: Number of routes going through load critical nodes

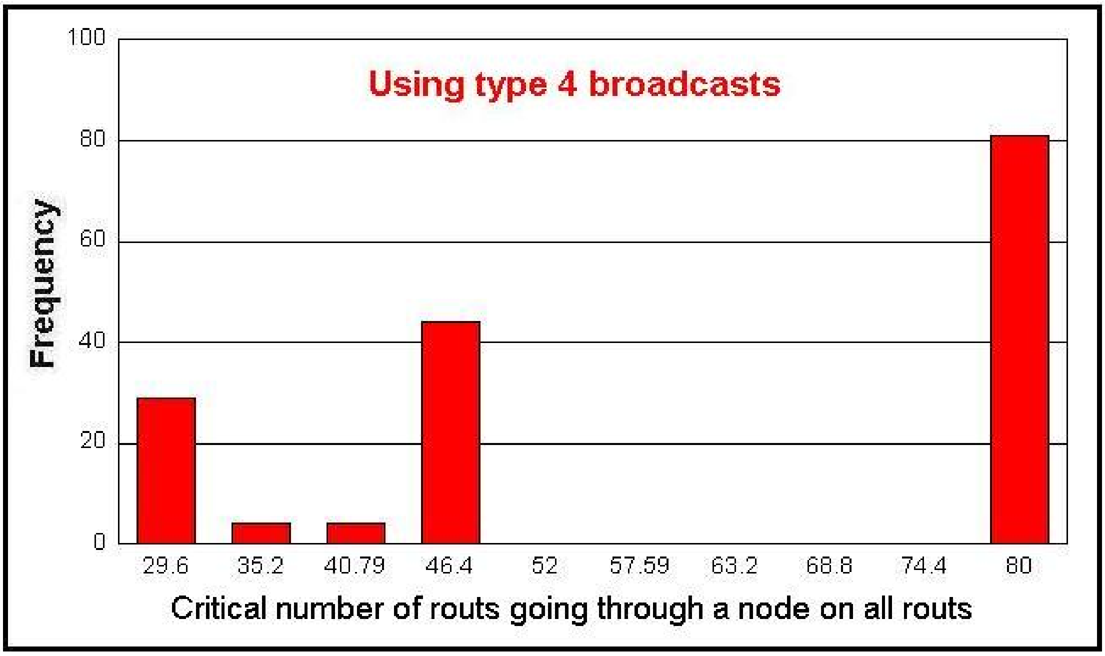


Fig. B.7: Distribution of the critical number of routes going through a node

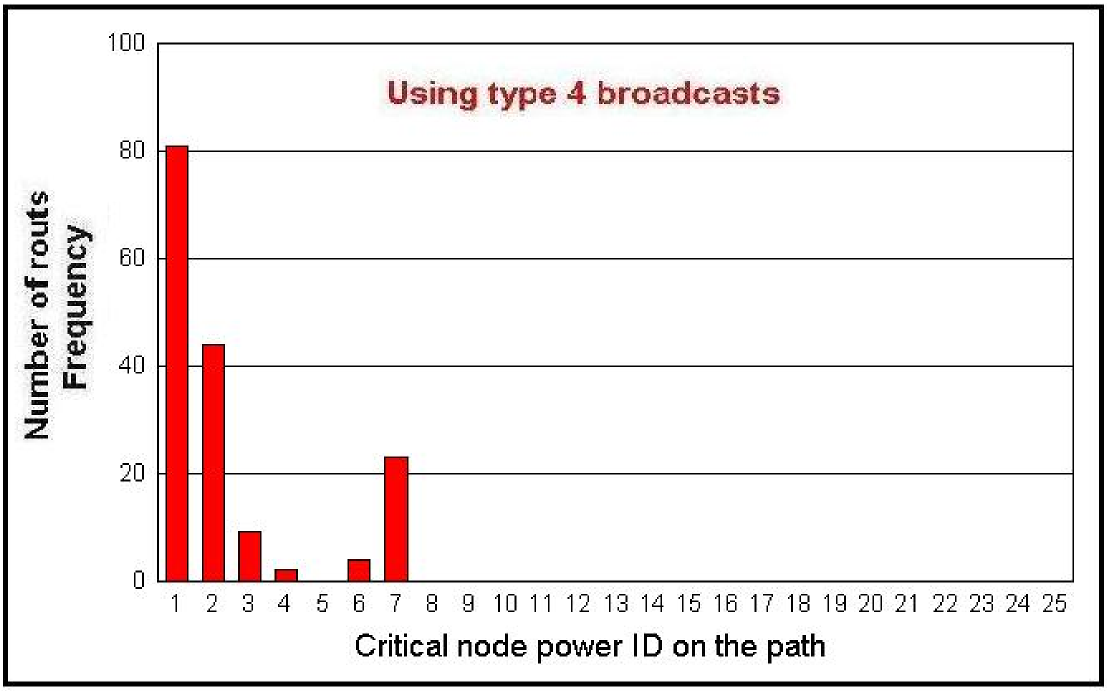


Fig. B.8: Number of paths going through power critical nodes

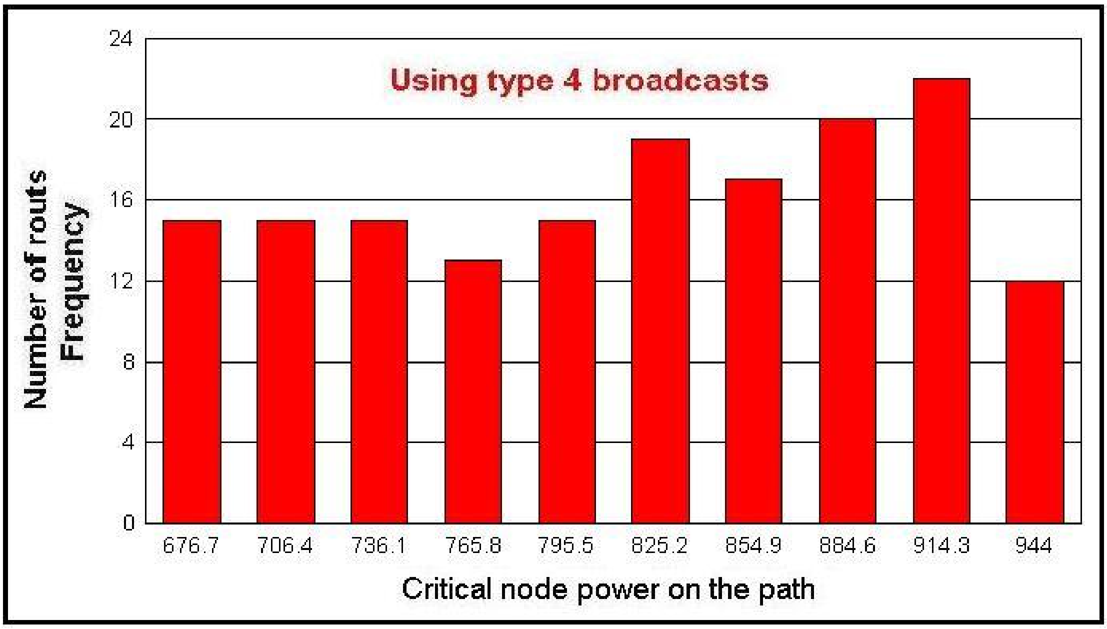


Fig. B.9: Power distribution for critical nodes