Master's Thesis

Title

An Adaptive Routing Protocol with Attractor Selection for Mobile Ad Hoc Networks

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Abstract

Mobile Ad Hoc Networks (MANETs) have various advantages over a traditional wired networks, e.g., requiring no fixed infrastructure and allowing arbitrary movement and participation of mobile nodes. However, routing in MANETs faces many difficulties, e.g., frequent topology changes and a multiple access medium which is easily interfered by other radio signals. Many MANET routing protocols have been proposed to handle these problems in the past. Unfortunately, they require a considerable amount of undesirable overhead especially in the unstable conditions like failures and mobility. Therefore, we aim at designing a MANET routing protocol which is adaptive against topology changes and packet collisions while having low overhead.

In this thesis, we propose a biologically-inspired routing protocol for MANETs. As biological systems are well-known for their self-adaptability against a changing environment, we adopt the biologically-inspired mechanism, called *attractor selection*, in the next hop selection process for routing in MANETs. Our protocol is a noise-driven and feedback-based on-demand routing protocol which is based on the previously proposed *mobile ad hoc routing with attractor selection* (MARAS). Unlike the original protocol, which uses a simplified packet level routing, we extend MARAS to fully operate within the IEEE 802.11 protocol stack without such limitations.

The main contribution of this thesis lies in the route maintenance mechanism performed by using a feedback packet for each delivered data packet. In respect to this mechanism, the route recovery can be achieved without using additional broadcast control packets like most of the on-demand routing protocols, e.g. AODV. Comparing to AODV, MARAS can achieve up to 48% higher delivery efficiency while having approximately 42% lower overhead in the failure scenarios. In mobility scenarios, MARAS and AODV have roughly the same performance. MARAS is also compared to another biologically-inspired protocol, AntHocNet, and is found to have much lower overhead. AntHocNet has higher delivery efficiency than MARAS only in the scenarios with low traffic and dynamics, but it is inferior to MARAS in the most cases of the evaluation.

Keywords

Ad hoc networks

Routing protocol

Biologically-inspired networking

Attractor selection mechanism

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1 Introduction

Mobile Ad Hoc Networks (MANETs) have been receiving a lot of research attention in the last few decades. MANETs differ from the traditional wired networks because they are independent of a fixed infrastructure; this allows the mobile nodes to move freely and makes many useful applications possible, e.g., rescue mission in an infrastructure-less area. However, this flexibility causes difficulties in routing. Examples of these difficulties are [1]:

1) Unpredictable dynamic changes in topology which is caused by the arbitrary movement and participation of the member nodes as shown in Figure 1.

2) Decentralized control as each node has to maintain the route locally with only partial network information.

3) Limited bandwidth as the wireless channel uses a multiple access method, e.g., CSMA/CA, and each transmission interferes with each other.

4) Limited energy of the mobile node.

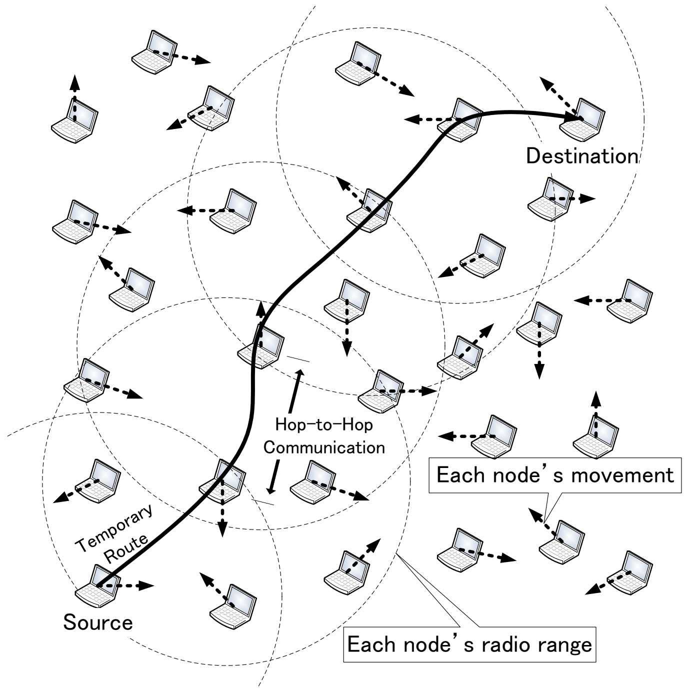


Figure 1: Communication in mobile ad hoc networks

Due to these difficulties, a routing protocol should not create high control overhead due to limited bandwidth and energy despite the need of control mechanisms for handling the network dynamics. Designing such routing protocols is a challenging task; therefore, one of the most active research activities on MANETs is on routing protocols.

Many MANET routing protocols have been proposed in the past and they can be distinguished into three main categories: *proactive*, *reactive*, and *hybrid* protocols. The proactive protocols exchange control messages between nodes periodically to maintain a consistent view of the network even when there is no active data session. This allows the proactive protocol to discover the route quickly at the price of large bandwidth consumption from the overhead in exchanging control message. Moreover, there is a waste of network resources because every node has to maintain the complete view of the network even though most routing information is never used. In contrast, the reactive protocols establish and maintain the route between the source and the destination only if there is a request. Because of this characteristic, these protocols are also called *on-demand* protocols. The established route is maintained as long as the data session is active. After a certain period of time, when the data session becomes inactive, the route is removed to release the occupied resources. Therefore, reactive protocols consume less bandwidth than proactive protocols. However, due to the dynamic characteristic of the ad hoc network, the packet might suffer a variable and long delay as the route discovery/recovery might have to be performed at each hop it travels through. To overcome these weaknesses of both proactive and reactive protocols, the hybrid protocols have been proposed. In hybrid protocols, groups of nodes—often called *zones*, are formed and a proactive routing method is used within each zone while a reactive routing method is used to communicate with remote nodes. Most hybrid protocols separate nodes into flat zones and a few use hierarchical structures like trees or clusters [2]. With this method, the overhead is reduced because the inefficient control overhead of the proactive approach is limited only within the zone and and the lower overhead from reactive routing is used to efficiently connect each zone. However, the performance of hybrid protocols often relies on the trade-off in parameters like the zone radius, which needs to be particularly adjusted to each network before use.

Examples of well-known proactive protocols are the destination-sequenced distance vector (DSDV), which offers a loop-free route by using the distance vector shortest path routing algorithm [3], and the optimized link state routing (OLSR), which attempts to reduce the flooding overhead by using optimized (partial) link state information [4]. Among the on-demand protocols, the well-known protocols are the dynamic source routing protocol (DSR) and the ad hoc on-demand distance vector routing (AODV). DSR requires low overhead as it does not require any periodic control messages and it can lower the route discovery overhead using a caching mechanism [5]. AODV uses a routing table at each node to achieve quick route recovery in dynamic conditions [6]. Examples of well-known hybrid protocols are the zone routing protocol (ZRP) [7] and the zone-based hierarchical link state (ZHLS) [8]. More details of existing MANET routing protocols and their features are discussed in Section 2.

We focus our research on on-demand protocols because they require less overhead than proactive protocols in order to adapt to changes in the network and proactive methods consume too much energy in exchanging the routing information on a periodic basis, especially pure proactive protocols like DSDV. In addition, it has been shown that DSR is better than OLSR in terms of energy consumption [9]. Among the on-demand protocols, AODV is more scalable and more adaptive than DSR as shown in [10]. However, AODV has its own weaknesses, i.e., it causes high load on the network because of routing overhead (mainly flooding) and it does not take the link qualities into account, which possibly results in selecting unstable links [11]. Therefore, we aim at designing a new routing protocol, which is more adaptive against unstable conditions in the network and causes lower overhead than AODV. Optimizing this newly proposed protocol by converting it into a hybrid protocol can be considered as a future work.

To achieve robustness and adaptability, we consider a biologically-inspired mechanism. As biological systems are well-known for their robustness and adaptability, there is a lot of research adopting mechanisms inspired by biology, e.g., swarm intelligence [12], which is a very active field of research, and ant colony optimization (ACO) [13], which is also based on swarm intelligence and useful for solving optimization problems. For MANETs, many biologically-inspired routing protocols have been proposed and most of them are based on swarm intelligence, e.g., AntHocNet [14], BeeAdHoc [15], and HOPNET [16]. Note that our protocol however uses a biologically-inspired mechanism from cell biology called *attractor selection* and is not based on swarm intelligence. The reason is that the concept of routing with the attractor selection mechanism has been found simple yet robust to failures [17, 18]. Moreover, our purpose is also to discover a new alternative of biologically-inspired mechanisms other than social insects-based swarm intelligence for MANETs.

Our adaptive mobile ad hoc routing with attractor selection (MARAS) is an extended work from [17, 18]. Unlike the original protocol, which focused only on the basic routing mechanism using simplified assumptions on packet level, we remove such limitations and evaluate MARAS with the QualNet network simulator [19], which fully operates in the IEEE 802.11 protocol stack. MARAS is a noise-driven on-demand protocol which uses feedback of delivered data packets from the destination for route maintenance. Using the feedback information along with the attractor selection mechanism allows MARAS to recover from link failures without issuing any additional broadcast control message like AODV. According to the evaluation results, in most scenarios MARAS has higher delivery efficiency than AODV and in failure scenarios with high node density it also achieves lower transmission overhead. MARAS has only slightly lower delivery efficiency and higher overhead per successfully delivered packet than AODV in mobility scenarios. We also compare MARAS to another biologically-inspired protocol—AntHocNet. The results show that MARAS has lower delivery efficiency than AntHocNet only in scenarios with low failure occurrences, low traffic load, or low node density. However, MARAS generally has much lower overhead than AntHocNet and it completely outperforms AntHocNet in the rest of considered scenarios of the evaluation.

The rest of this thesis is organized as follows. First, we present some of the most important routing protocols for MANETs in the next section. Then, we introduce the attractor selection mechanism and the derived mathematical model in Section 3. Afterward, we describe our protocol in Section 4. In Section 5, the evaluation results are presented and discussed. Finally, we conclude and list future work in Section 6.

2 Related Work

In this section, we introduce the related research on routing protocols for mobile ad hoc networks. First, we start with the conventional routing protocols and then also discuss the biologically-inspired approaches. Protocols discussed in this section are shown in Table 1.

Table 1: Summary of MANET routing protocols

Conventional Routing			**Biologically-inspired Routing**
Proactive	**Reactive**	**Hybrid**	
DSDV, WRP, FSR, GSR, OLSR, OFLSR	AODV, DSR, ABR	ZRP, ZHLS	AntHocNet, BeeAdHoc, Termite

2.1 Conventional Routing Protocols

Since the first proposal of MANETs, there have been continuous research attempts to solve routing problems in MANETs. Many routing protocols have been proposed, evaluated, and implemented by researchers all over the world. The well-known protocols from both general research and standardization by the Internet Engineering Task Force (IETF) are discussed in this section. Similar to literature reviews in many studies, e.g., [16, 20], conventional MANET routing protocols are classified into 3 categories: proactive, reactive, and hybrid, as explained below.

2.1.1 Proactive Routing Protocols

In proactive routing protocols, each node attempts to maintain the routing information to every other node by periodically exchanging control messages. There are many proactive routing protocols and various methods to maintain the routing information. However, they can be classified into 2 categories: *distance vector* and *link state*.

Distance vector routing protocols select the path based on the relayed link cost from every other node in the network. In this kind of protocols, every node advertises its directly connected links and their costs along with the relayed link information and costs received from other nodes.

One example of distance vector routing protocols is the *destination-sequenced distance-vector protocol* (DSDV) [3], which uses the number of hops to the destination as the cost. The routing information is advertised in a broadcast manner throughout the network along with the sequence number, which is originally generated by the destination. The sequence number is used to avoid a routing loop problem which is a common problem in distance vector routing. DSDV reacts to the topology changes using two kinds of update packets: *full dump* and *incremental*. The full dump packets will carry all available routing information at the current node to another while the incremental packets will carry only the information changed since the last full dump. These two types of routing update packets are used to lower the overhead and shorten the update latency. However, the overhead of DSDV is still large due to the large amount of periodic update information, which makes DSDV not scalable [2].

Another example is the *wireless routing protocol* (WRP) [21]. In WRP, each node maintains four tables: a distance table, a routing table, a link-cost table, and a message retransmission list. WRP uses the predecessor information along with the sequence number to avoid routing loops. In addition to the bandwidth consumption overhead, WRP also has a high memory consumption overhead due to the large amount of information maintained at each node.

Link state routing protocols maintain a complete view of the network and construct a routing tree for data packet forwarding. To obtain a complete network view, a large amount of routing information is exchanged among nodes. Similar to distance vector protocols, link state protocols also have a high overhead where a large amount of bandwidth is consumed by routing control packets.

One example of link state routing protocols is the *fisheye state routing* (FSR) [22, 23]. FSR maintains a topology map at each node by exchanging the link state information between neighbor nodes. However, the link state packets are not broadcasted and only periodically exchanged with the local neighbor nodes. FSR reduces the amount of control overhead by removing the event-based link state update and using only the periodic update. Moreover, the periodic update frequency is reduced by the fisheye technique where the node within the smaller scopes updates more frequently than the node that is farther away. FSR is based on the global state routing (GSR) [24], which can be viewed as a special case of FSR where the scope is ∞. The advantages of FSR are that the flooding is minimized and the routing is more accurate for nodes closer to the destination, which makes it suitable for dense networks. However, the slower update for remote nodes affects the accuracy and by using this imperfect topology information an inaccurate route selection could possibly occur.

Another example is the *optimized link state routing* (OLSR) [4]. In OLSR, each node periodically floods a list of its 1-hop neighbors. However, instead of relaying all link information, OLSR diffuses only the partial link information through the multipoint relays (MPRs) which cover all 2-hop neighbor nodes. Therefore, the complete topology can be obtained while the amount of link state information is reduced. However, flooding the 1-hop neighbor list at each node is still not suitable in MANET and causes high overhead in large networks. Regarding this, there is a proposal of the FSR-OLSR combination which is called OFLSR (or F-OLSR) [25] in the field of wireless mesh networks. According to the evaluation in [26, 27], OFLSR offers higher delivery ratio and lower delay than AODV which is a reactive routing protocol. However, the overhead of OFLSR is still much higher than AODV.

In summary, most of the proactive routing protocols are not well scalable due to the amount of routing control overhead. The delivery efficiency and delay are generally better than reactive routing protocols by exploiting this extra amount of overhead. Many attempts have been made to reduce the overhead and one of the considerably successful methods is hierarchical routing like OLSR. However, the selection of representative nodes, like MPR in OLSR or cluster heads in other hierarchical routing is also a disadvantage of this kind of routing protocols in a mobility scenario. As a result, it may require more overhead in MANET where mobility is one of its characteristics. Additionally, maintaining all the link information can be considered unnecessary because most of the links are not used. Regarding this matter, reactive routing protocols can be considered more suitable in MANETs.

2.1.2 Reactive Routing Protocols

Reactive routing protocols, also known as on-demand routing protocols, have been proposed to reduce the number of control overhead by maintaining only the information for active routes. Instead of maintaining all the routes at all times, the protocol starts route discovery on-demand. In the route discovery process, a route request packet (RREQ) is usually flooded until it reaches the destination (or a node that contains the route to the destination). Then, a route reply packet (RREP) is generated and sent back to the source to inform the available route. This route is maintained as long as the connection is active and removed once it is no longer required. In general, on-demand routing protocols can be classified into 2 categories: *hop-by-hop routing* and *source routing*.

Hop-by-hop routing protocols maintain the routing information locally at each node. The data packet stores only the destination address in its header and each intermediate node will use its routing table to forward the packet to the specified destination. The advantage of this approach is the high adaptability of the path because each node can react to the changes in the network faster than the end-to-end manner. However, maintaining the routing information at each node requires higher routing overhead and resources.

An example of hop-by-hop routing protocols is the *ad hoc on-demand distance vector routing* (AODV) [6]. The standard AODV uses the broadcast route request packet to discover the route to the destination. Once the route request arrives at the destination, the route reply packet is sent back to the source using the reverse route previously established by the route request packet. AODV uses a blacklist to avoid using unidirectional links, which are the links established by the route request packet but cannot be utilized by the route reply packet. Moreover, the precursor list is maintained to keep track of the upstream node that is utilizing this route. When a route failure occurs, a route error packet is sent out in broadcast manner if the precursor list is not empty. This route error packet is repeatedly flooded until it reaches the source node or the node with an empty precursor list. Once the source node receives the route error packet, the route recovery which is the same process as the route establishment using route request and route reply packets is repeated. Regarding the route recovery process, the local route repair feature of AODV can be chosen. Instead of re-initiating the route discovery from the source, the delay can be reduced by initiating it from the node that detects the error. Also, another feature of AODV which allows the intermediate nodes to respond to the RREQ can be chosen to further shorten the delay.

Source routing protocols maintain the routing information only at the source. A list of addresses that the packet will traverse until it reaches the destination is embedded into the header of each packet by the source. Each intermediate node has no knowledge of the route to destination and only forwards each data packet by the information in its header. As maintaining the route at each intermediate node is no longer required, the overhead is reduced. However, the probability of route failures could be high when the path becomes long in large networks or when there is a high level of mobility. Moreover, the overhead of embedded route information in the header also affects the performance in large networks. According to these disadvantages, it can be clearly seen that source routing protocols do not scale well.

An example of source routing protocols is the *dynamic source routing* (DSR) [5]. DSR is a simple source routing protocol composed of two mechanisms: route discovery and route maintenance. Both mechanisms operate purely reactive, which means that if there is not any change in the network, then there will be no additional control packet. DSR supports multiple routes which help decrease the delay upon the failure of the currently used route. Other than source-initiated flooding route discovery, each node allows to cache the overheard embedded route information in each data packet which increases the number and freshness of possible routes. When any link on a route is broken, a route error packet (RRER) is sent back to inform the source. Upon the RRER arrival, the broken route is removed and another available route will be selected or the route discovery process will be re-initiated. According to this behavior, DSR should have a very low routing overhead. It has been shown in [10] that DSR performs better than AODV in terms of delay and overhead in a less "stressful" scenarios, e.g., low number of sources, low mobility, etc. However, AODV performs better than DSR in terms of delay but still has higher routing overhead in a more stressful scenario, which is more likely to occur in real world applications.

Another source routing protocols is the *associativity-based routing for ad-hoc mobile networks* (ABR) [28]. ABR is a special case of source routing protocols because it uses a similar route discovery to DSR but also maintain local route information like AODV. Rather than having multiple backup routes like DSR, ABR focuses on the stability of the route. ABR selects the route based on a metric, called associativity tick, which reflects the degree of association stability of mobile nodes. The associativity ticks are maintained by periodic beacons from each node. During the route discovery, not only the addresses are embedded in the packet's header but also the associativity tick is included to allow an intermediate node and the destination to select the best path according to all associativity ticks of upstream nodes. As ABR does not have backup routes, a route reconstruction is required upon link failures. Even though this route reconstruction is performed locally, it can still cause a longer delay and more control overhead.

In summary, reactive routing protocols generally require less overhead than proactive routing protocols as they maintain only necessary routing information. In [9], it was shown that DSR achieves lower overhead, higher throughput, and longer node lifetime than OLSR over variable mobility and connection patterns. On the other hand, the only strong point of OLSR is the shorter delay as it is the common advantage of proactive routing protocols. According to this research, it can be seen that in general reactive routing protocols are more suitable than proactive routing protocols except where the application requires very short delays. When comparing among different reactive protocols, AODV is more adaptive than DSR as it can maintain higher throughput and shorter delays in the network scenarios with higher dynamics [10]. As we focus on the adaptability of the routing protocol, we use AODV as the reference protocol in this thesis.

2.1.3 Hybrid Routing Protocols

Hybrid routing protocols use the combination of proactive routing and reactive routing concepts for the purpose of increasing scalability. In hybrid protocols, the network is partitioned into zones. A proactive routing method is used within each zone while a reactive routing method is used to communicate with nodes that are outside of the zone. With this method, the overhead is reduced because the inefficient control overhead of the proactive approach is limited only within the zone and the lower overhead from reactive routing is used to efficiently connect each zone. In this section, we show four examples of hybrid routing protocols as follows.

The first example is the *zone routing protocol* (ZRP) [7]. ZRP reduces the proactive routing overhead by limiting the scope of proactively maintaining the routing information within a zone. A zone is defined by the hop distance between nodes where the nodes within ρ hops from the current node are in the same zone. ZRP discovers the path to the node outside the zone using bordercasting, which also reduces the number of flooding messages. In bordercasting, the route request packet is forwarded only by the border node of the current zone. When the route request packet is received, the border node looks up the proactive routing table in its zone and sends back the route reply packet if it has the route to the destination or repeats the bordercasting process otherwise. The routing zone radius ρ is a very crucial parameter in ZRP which also becomes a disadvantage of ZRP. The radius ρ must be carefully chosen based on the characteristic of the network. If the radius is too large, then ZRP behaves more like a pure proactive protocol. On the other hand, if the radius is too small, then ZRP behaves more like a pure reactive protocol. In both cases, ZRP loses its advantage of reduced overhead and scalability.

The second example is the *zone-based hierarchical link state* (ZHLS) [8]. ZHLS is a zone-based hierarchical link state routing protocol, which also uses the location information from the global positioning system (GPS). In contrast to ZRP which defines overlapping zones, ZHLR utilizes the location information to partition the network into non-overlapping zones and assign each node a node ID and a zone ID. The hierarchical topology consists of two levels: a node level and a zone level. There is no cluster-head in ZHLS because the zones are pre-designed with regard to their location information. Hence, a single point of failure or bottlenecks can be avoided in ZHLS despite being a hierarchical routing protocol. The routing mechanism consists of intrazone proactive routing and interzone reactive routing which is similar to ZRP. Therefore, the similar advantages can be achieved. Additional advantages of ZHLS are the fixed zone location. Once the source node knows the node ID and the zone ID of the destination, even if the link breaks, ZHLS can still easily find another route to the destination with less overhead compared to reactive routing protocols. However, this fixed zone location is also the disadvantage of ZHLS as it is required to be preprogrammed before use.

In summary, hybrid routing protocols use the integration between proactive and reactive protocols to increase the scalability. Lower delay and overhead can be expected from this kind of protocols even in large scale networks. However, our research objective is to design an adaptive routing protocol. It should be able to adapt to any network without any adjustment. On the other hand, hybrid routing protocols require proper tuning of parameters, like routing zone radius in ZRP or preprogrammed zone maps in ZHLS for each network. Therefore, we do not rely on the hybrid routing approaches in our protocol.

2.2 Biologically-inspired Routing Protocols

As stated above, the traditional routing protocols face a lot of problems due to the dynamic behavior and resource constraints in MANETs. To overcome this limitation, a routing protocol is required to have a self-organizing or an autonomous feature. An approach to achieve such feature is to use a biologically-inspired mechanism.

Once we look into the nature, a living organism, or a biological system, it can be seen that they can maintain their stable condition by themselves regardless of the external influences or dynamic conditions. For example, the human immune system can fight against the external threats, like virus or bacterias, to recover the body to normal state without any explicit control from the brain. In biological systems, each small entity works separately to lead the entire system to an equilibrium condition. One of the biological systems that have received a lot of research attention is swarm intelligence [12].

The concept of swarm intelligence originates from the social behavior of insect colonies, such as ant colonies. We explain some swarm intelligence-based routing protocols in this section. First, the ant-based routing protocols are discussed. Afterward, we describe the other social insect-based routing protocols.

The main algorithm of ant-based routing protocol is the Ant Colony Optimization (ACO) [13]. ACO is based on the foraging process of ants which is a random walk when searching for food. Once the food is found, the ant returns to the nest via its own trail. While returning, the ant deposits pheromones on the way as chemical markers for other ants to follow its trail to the food. The indirect communication, which is based on the pheromone trail mediated by the environment, is called *stigmergy*. Using this approach, the shortest path between the source and the destination can be found.

The first ant-based routing protocol, called AntNet [29], is designed for a wired network. AntNet uses two kinds of agents, forward and backward ants, to find the shortest path. The forward ant moves toward the destination d via a neighbor node n according to a greedy stochastic policy based on the ant's visited node list, the pheromone information P_{nd}, and the heuristic function l_n based on the queue length of the link connecting to neighbor n. To avoid congestion, the forward ant is released based on the probability value p_d which changes according to the current traffic load. At the destination, the forward ants turn into the backward ants and return to the source on the same path the forward ants had taken. While returning, the pheromone information and other statistical information gathered by forward ants are used to update the routing table of each intermediate node.

The early attempt of applying ACO on MANET routing is the *ant-colony based routing algorithm for MANETs* (ARA) [30]. Even though ARA is based on the same ACO as AntNet, it is a reactive routing protocol consisting of three phases: route discovery, route maintenance, and route failure handling. ARA sets up the path reactively using the forward ant (FANT) and the backward ant (BANT) in the route discovery process. Different from the original ACO, the agent in ARA does not memorize the visited nodes. Instead, each intermediate node uses the source and the previous hop of the FANT and creates the route entry accordingly. Routing loops are avoided by using a sequence number like in other reactive protocols. The route maintenance is performed using the reinforcement by data packets. The failure handling re-initiates a route discovery when there is no alternative link in the routing table.

Another well-known ant-based routing protocol is the *ant-based hybrid routing algorithm for mobile ad hoc networks* (AntHocNet) [14], which uses both pheromone and visited node list similarly to AntNet. In AntHocNet, the route is set up reactively using *reactive forward ants* which gather the path quality while travelling in the network. Upon arrival at the destination, *backward ants* return on the path taken by forward ants to the source and update the routing tables of nodes on the path. Unlike ARA, AntHocNet uses *proactive forward ants* to maintain the paths. These ants follow the pheromone information in the same way the data packets do but they have a small probability of being broadcasted. Therefore, better exploration of new paths can be achieved. A scalability improvement of AntHocNet has been proposed in the *hybrid ant colony optimization routing algorithm for mobile ad hoc network* (HOPNET) [16], which uses AntHocNet as a reactive mechanism for routing between zones.

Beside ant-based routing protocols there are other social insect-based routing protocols like BeeAdHoc and Termite. BeeAdHoc [15] is inspired by the behavior of dancing bees. It uses packer, scout, and forager bees that can be compared to data packet queue, forward ants, and the reinforcing data packets in ARA. The scouts are broadcasted to the destination to find routes and the foragers evaluate the paths to make a routing decision based on two metrics: delay and lifetime. Termite [31] is inspired by the hill building behavior of termites. Termite uses broadcast route discovery packets to find the route to the destination and at the same time distribute the source's pheromone. The route reply packet is routed back to the source using the distributed pheromone information the same way as the data packets. The visited node list is not maintained in any packet and the loop avoidance is done by memorizing the incoming packet ID at each node.

As mentioned in AntHocNet [14], the attempt to lower the overhead of ant-based routing in ARA results in a loss of exploratory behavior. Also, there is a lack of loop-free route maintenance in ARA. According to both protocols' evaluations, there is no significant difference in performance. Therefore, we use AntHocNet as another reference protocol in our evaluation to compare our protocol to a more complete ACO-based biologically-inspired mechanism.

3 Attractor Selection-based Mathematical Model

In this section, we introduce the background of the adopted biologically-inspired mechanism and our derived mathematical model. Additionally, we explain the notation that will be used in the rest of this thesis.

3.1 Attractor Selection Mechanism

The attractor selection mechanism is modeled after the behavior of *E. coli* cells, which is capable of adapting to dynamically changing nutrient conditions in the environment without an embedded rule-based mechanism [32]. A mutant *E. coli* cell has a metabolic network consisting of two mutually inhibitory operons which synthesize two corresponding nutrients. When one of the nutrients becomes scarce, the mRNA concentration of the operon that controls the missing nutrient increases to return the cell to a stable condition. However, there is no explicit rule-based mechanism to switch the mRNA concentrations of both operons. In [32], a model describing this bistable behavior of mRNA concentration m_1 and m_2 is proposed as

$$\frac{dm_1}{dt} = \frac{s(\alpha)}{1 + m_2^2} - d(\alpha)m_1 + \eta_1 \tag{1}$$

and

$$\frac{dm_2}{dt} = \frac{s(\alpha)}{1 + m_1^2} - d(\alpha)m_2 + \eta_2, \tag{2}$$

where $s(\alpha)$ and $d(\alpha)$ are the rate coefficients of mRNA synthesis and degradation, respectively. Both of them depend on α which represents the cell activity or cell volume growth. The η_1 and η_2 are independent white noise in gene expression.

According to [32], the equilibrium conditions in the metabolic network are called *attractors*. Since the biological systems are dynamic, there are changes in the system all the time. For example, when the cell becomes unstable by external influences or internal noise, its gene expression state will be driven to other attractors to return the cell to a stable condition. As there are more than one possible stable conditions, there is a mechanism to select a suitable attractor among multiple attractors, which is called attractor selection.

Additionally, we extend the model from two alternatives to M alternatives based on the Eqn. (1) and (2). Let m_i be the value representing if the i^{th} choice should be selected. Furthermore, let us define the M-dimensional vector $\vec{m} = (m_1, \ldots, m_M)$. The attractor selection

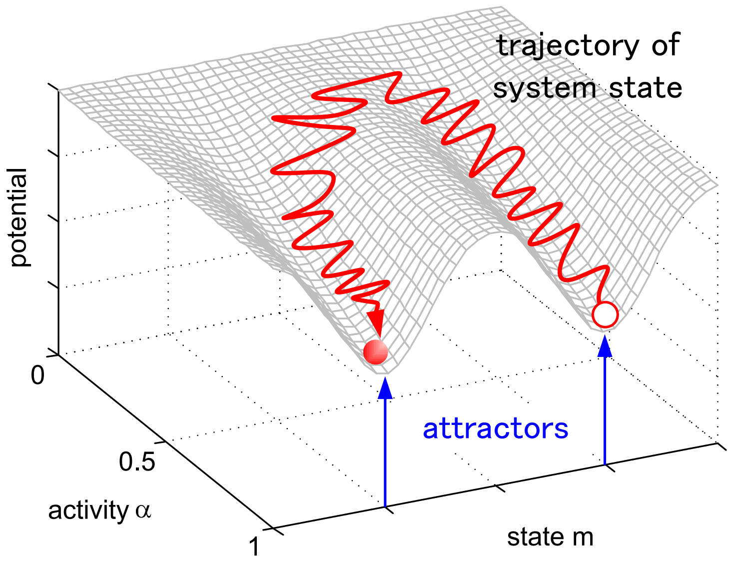


Figure 2: Behavior of attractor selection system

among M alternatives shall have the general form as

$$\frac{d\vec{m}}{dt} = f(\vec{m}) \times \alpha + \vec{\eta}, \tag{3}$$

where α expresses the goodness of the current condition and $\vec{\eta} = (\eta_1, \ldots, \eta_M)$ is the vector of the noise affecting the selection.

The activity α is the main parameter which controls the influence of randomness on attractor selection. When the current condition of the system becomes unstable, the activity decreases. As a result, the value of term $f(\vec{m}) \times \alpha$ will decrease and a larger effect from noise $\vec{\eta}$ will take place to allow the system to use a random walk to switch to another attractor. Once the system reaches a suitable attractor, the activity will increase and the effect of noise will be suppressed, which then allows the system to become stable again.

In Fig. 2, we show the general principle of the attractor selection concept. The x-axis shows a state m, where some possible states of m are the attractors, the y-axis is the activity α, and the z-axis indicates the energy potential defined by $f(m)$. The current system state is illustrated as a circle which is constantly in motion due to the effect of the noise. It can be observed that when the activity is high, changing the system's state is difficult because of the steepness of the potential landscape. On the other hand, when the activity is low, the landscape becomes smoother and changing the state can be achieved easier by only the small effect of noise.

At first, the concept of having noise in the system may look undesirable. However, adding noise into the system makes it in general more robust to external fluctuations. It has been discovered that noise and random walk can provide load-balancing and scalable properties in sensor networks [33]. Additionally, local minima in local search problems can be avoided using noise and random walk as explained in [34].

3.2 Mathematical Model for MANET Routing Protocol

The attractor selection is adopted in our protocol for next hop selection among neighbors. Hence, we map the vector of neighbors to $\vec{m}$, which contains value m_i, called *state value*, indicating if the neighbor i^{th} should be selected among M neighbors and map activity α to the information which shows the goodness of the current routing condition. Moreover, as we consider unicast traffic between the source and the destination, the selection shall select a single next hop neighbor at a time. Therefore, we design the attractor selection function to provide only single distinguished high value as follows.

For all neighbor i:

$$\frac{dm_i}{dt} = \frac{s(\alpha)}{1 + m_{max}^2 - m_i^2} - d(\alpha)m_i + (1-\alpha) \times \eta_i, \quad (4)$$

where

$$\begin{aligned} m_{max} &= \max_{j=1,\ldots,M}(m_j), \\ s(\alpha) &= \alpha[\beta\alpha^\gamma + \varphi^*], \\ d(\alpha) &= \alpha, \\ \varphi^* &= 1/\sqrt{2}, \end{aligned}$$

and η_i is the white noise. Parameters β and γ control the influence of activity over state values and we use empirical values $\beta = 10$ and $\gamma = 3$ throughout this study. The term $(1-\alpha)$ additionally suppresses the effect of noise when the activity is high.

In the case that the activity α is high, the Eqn. (4) gives the $\vec{m}$ which has a single high value and $M-1$ low values. This means that only one neighbor will be selected as the next hop as only the maximum value is selected in our protocol. While in the case that activity α is low, the Eqn. (4) gives a random $\vec{m}$ where each member m_i has roughly the same value. This gives another

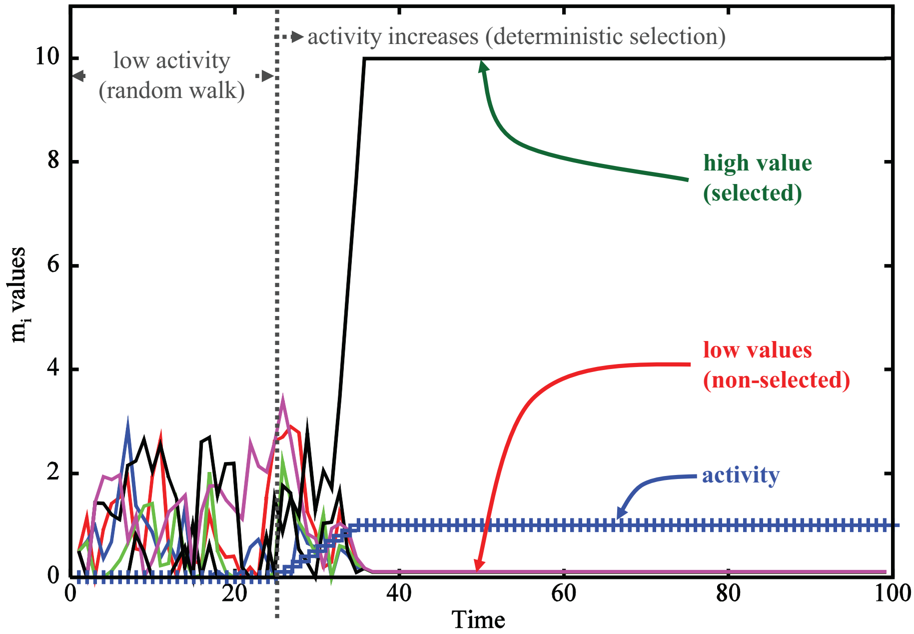


Figure 3: Dynamics of M alternatives' values from attractor selection model ($M = 6$)

non-selected value a chance to become the maximum value easily requiring only small effect of noise. Therefore, according to this approach, the appropriate selection can be found.

The dynamics of M alternative values from Eqn. (4) is shown in Figure 3 where the solid lines represent the m_i values while '+' line represents the activity α.. From the time $t = 0$ to 25, the α is low, therefore, each value m_i receives more effect from noise and has a random value. When the solution is occasionally found, i.e., after time $t = 26$, α starts increasing. Therefore, the gap between selected value and non-selected values grows larger and becomes stable with one high value and $M - 1$ low values once the $\alpha = 1.0$ which indicates that the system reaches the suitable attractor.

4 Mobile Ad Hoc Routing with Attractor Selection (MARAS)

MARAS is an on-demand routing protocol which sets up the route upon request. We assume the bidirectional connectivity between each pair of neighbor nodes. In MARAS, each node maintains its own routing table and neighbor list. According to the overview of MARAS shown in Figure 4, first, MARAS establishes the route between the source and the destination using a similar approach as AODV which is explained in detail in Section 4.1. The information stored at each node is described in Section 4.2. After the route is set up, the data packets are forwarded to the destination by using the information stored in the route entry (see Section 4.3). Once the data packet arrives at the destination, the feedback packet is sent back to the source for route maintenance. Feedback packets are used to evaluate the path that the data packets have taken and notify the path condition to each node on the path. At each intermediate node, by using the information from the feedback packet, the activity is calculated and the routing information is updated. Moreover, to ensure that the selection uses only the information that is refreshed by recent feedback packets, the activity is constantly decayed over time to avoid using the outdated information. Even though the bidirectional connectivity is assumed, MARAS can operate in the network containing unidirectional links. The reason is that the unidirectional link will not be selected as it will never be updated by the feedback packet. Further details of routing maintenance mechanisms are explained in Section 4.4.

4.1 Route Establishment

We adopt the broadcasting route discovery mechanism from AODV and make a few modifications. In our protocol, when a node has data to send, a *route-request packet* (RREQ) is broadcasted from the source node and re-broadcasted until it reaches the destination. Each RREQ packet has a unique ID, which is used to detect and drop a duplicated RREQ packet. The previous hop of a valid RREQ packet is memorized for sending the route reply packet back to the source in the future.

When the RREQ packet arrives at the destination, a *route-reply packet* (RREP) is generated. As the reverse path for the RREP packet is memorized, it is forwarded in unicast manner to the source. On reception of the RREP packet at any intermediate node, that particular node sets up the route entry for the source of RREP—the destination of corresponding RREQ, with only the

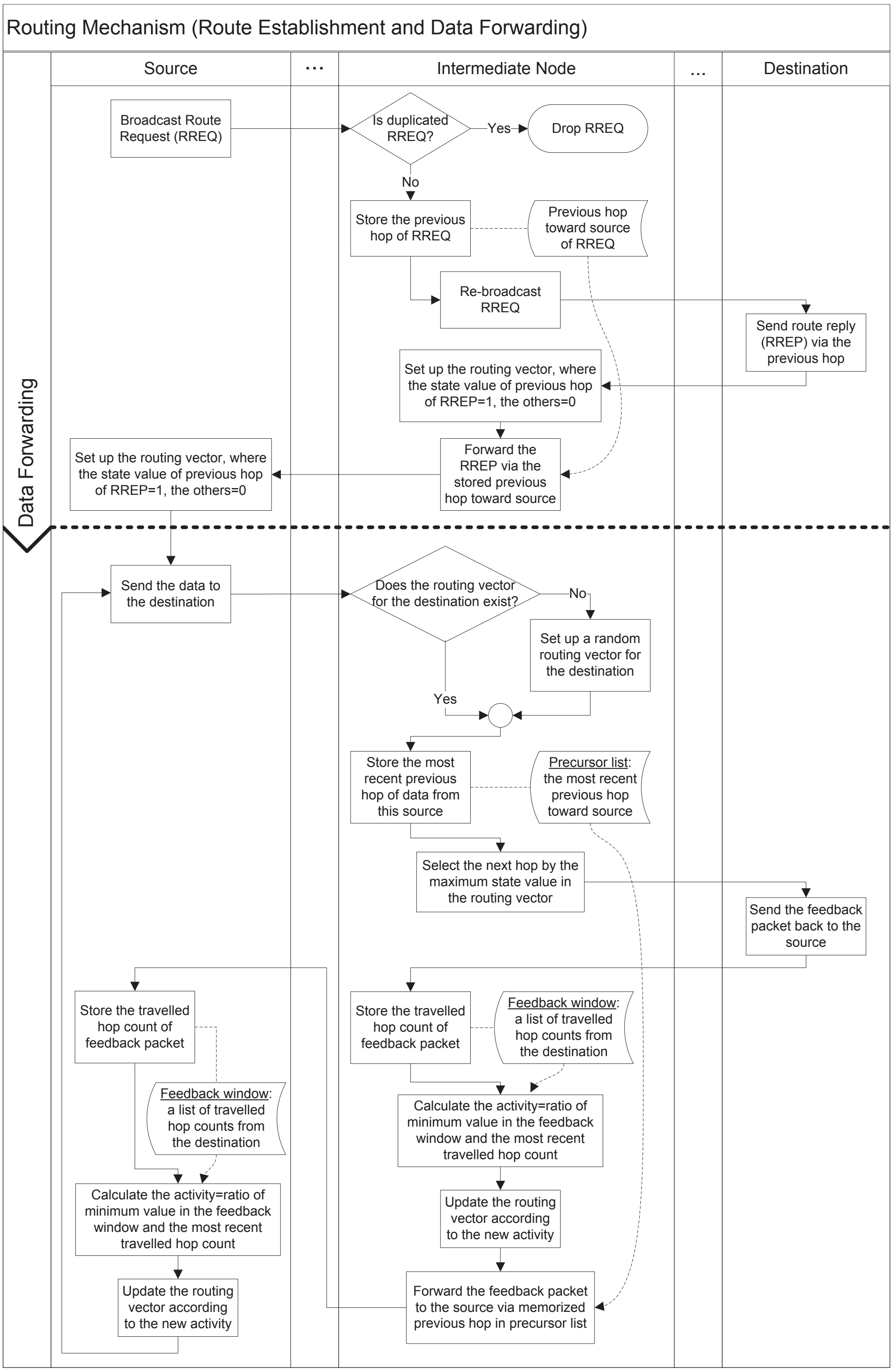


Figure 4: Overview of MARAS

previous hop neighbor having a state value equal to 1 (all others are 0), and the highest activity value $\alpha = 1$. In case that the route entry already exists, the attractor selection vector and the activity are re-initialized. Afterward, the RREP is forwarded again via the memorized neighbor. Once the RREP arrives at the source node, and after updating the activity and the routing vector in the same manner at all intermediate nodes, the data packet forwarding begins.

On reception of a data packet at an intermediate node, if the current node has no route entry for that destination, then it will set up a new random vector which contains equal state values $m_i = \lambda$ for every neighbor i and starts the random walk mechanism.

4.2 Routing Information

The routing information stored at each node in the route entry are

(1) Destination address

A destination address is used for looking up the corresponding route entry when a data packet is received.

(2) Neighbor vector $\vec{n} = (n_1, n_2, \ldots, n_M)$

A neighbor vector contains a list of neighbor addresses, maintained by the HELLO packet mechanism explained in Section 4.4.5.

(3) Attractor selection vector, called *routing vector* $\vec{m} = (m_1, m_2, \ldots, m_M)$

A routing vector has the same dimension as the neighbor vector and contains the *state values* of each neighbor node. A state value is mapped to an neighbor address in the neighbor vector in order. These state values Are used by the attractor selection mechanism to select the next hop for forwarding a data packet to the destination.

(4) Activity α

An activity shows the current goodness condition of the path to the destination. The routing vector is updated according to this value, allowing the next hop selection to adapt to the current condition.

(5) Precursor list

A precursor list contains pairs of the address of the source node, which sends the data packet via the current node, and the address of the most recent neighbor that forwarded the data packet originated at that source node to the destination via the current node.

(6) Feedback window

A feedback window is a sliding window where each frame contains the travelled hop count of the feedback packet which is originated at the destination and sent via the current node. Each frame is added to the feedback window on the reception of a feedback packet and will be deleted after T s. This information is used to calculate the activity which is explained in Section 4.4.1.

4.3 Data Packet Forwarding

The next hop selection in data packet forwarding is controlled by the attractor selection mechanism. Using attractor selection, MARAS selects the neighbor which has the *maximum state value* in the routing vector as a next hop. The data packet is forwarded to this next hop and the process repeats itself until it reaches the destination. The next hop is selected by the maximum state value as it shows the highest potential of that neighbor on delivering the data packet to the destination.

The concept of attractor selection along with the maximum state value favors the next hop selection in a way that, MARAS will keep selecting the same next hop as long as the activity is high. When the activity drastically decreases, the noise will increase the other candidates' state values to allow the selection of a different neighbor. Hence, MARAS is able to quickly recover from the undesirable conditions.

An example of the next hop selection for data packet forwarding is shown in Figure 5. Starting for the source Src to the destination Dst, the selected next hops are in the order of F and I. When observing the maximum value and the activity in the routing table of F and I, it can be seen that the maximum value decreases in lower activity α case and the gap between high value and low values becomes closer. If the activity keeps decreasing, then there will be a change of the maximum value and the new next hop will be selected. Additionally, the previous hop's state value is set as 0 to prevent the unfavorable backward selection.

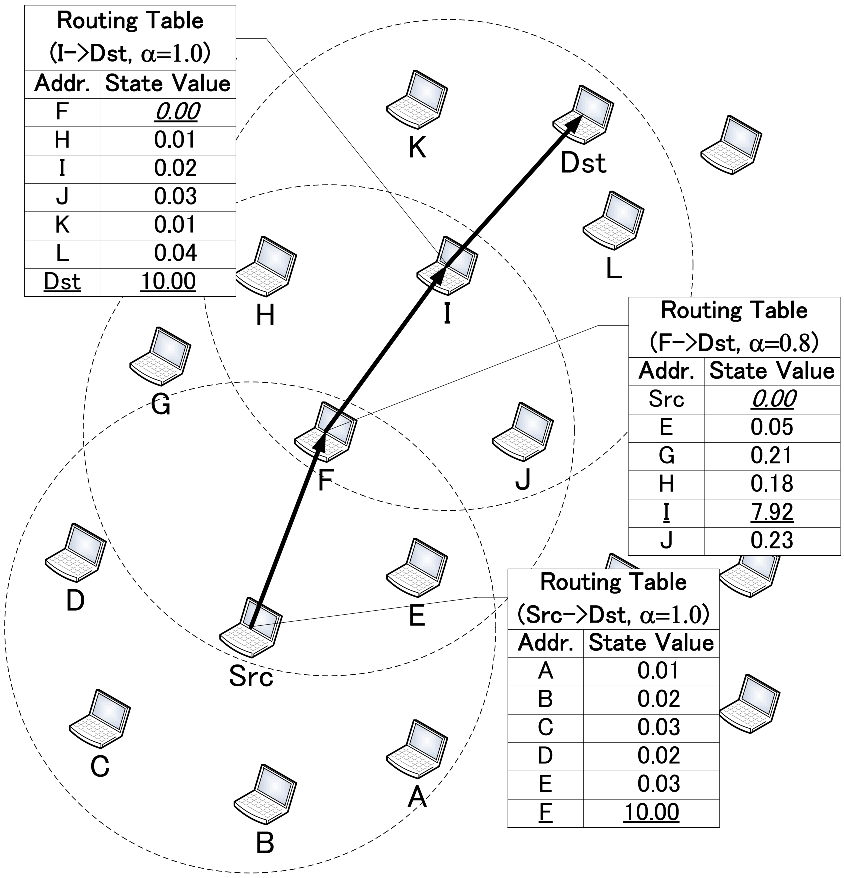


Figure 5: Example of the next hop selection using state values

4.4 Route Maintenance

MARAS maintains the same route as long as it is being used and removes unused route entries after a period of time to save the memory resource and the bandwidth required to maintaining it. In order to keep the routing information up-to-date, MARAS uses the feedback packet to learn the current condition of the network. Moreover, it updates the routing vector using a calculated activity to adapt the next hop selection according to the current network condition.

4.4.1 Feedback Packet

Upon the data packet arrival at the destination, a feedback packet is generated and sent back to the source. The feedback packet exploits the *memorized previous hop* in the precursor list at each intermediate node to take the most recent route back to the source and avoid getting lost. During its journey, it leaves its travelled hop count information in each intermediate node's *feedback window* for the purpose of activity calculation. The feedback window is the sliding window which keeps the hop count to destination and deletes this hop count after *window interval* T to avoid using the outdated information.

4.4.2 Activity Calculation

The activity of each routing vector is calculated upon the feedback packet arrival based on the most recent feedback packet's travelled hop count and the minimum travelled hop count in the feedback window. The activity is calculated on arrival of the feedback packet at time t_0 using the following equation:

$$\alpha(t_0) = \frac{\min_{t_0 - T < t \leq t_0} w(t)}{w(t_0)}, \qquad (5)$$

where $w(t)$ is the travelled hop count of the feedback packet which arrives at time t. Until the next arrival of the feedback packet, $\alpha(t_x) = \alpha(t_0)$, where $t_x \geq t_0$.

This activity changes according to the hop count to the destination in the range between 0 and 1. If the hop count to the destination becomes larger, then it means that the current path to the destination is unstable, i.e., link failure or node movement occurs, and the attempt to find a better path should be made. Therefore, the activity will decrease in such situation and the effect from noise will induce a random walk. On the other hand, once a shorter path is found, the $\alpha(t)$ will immediately become 1, and MARAS will keep using this path until another change occurs in the network.

With this activity definition, the attractor selection operates with only the information from the last T seconds. This parameter T is crucial to the performance of the protocol as outdated information problem could be taken into account, if it is too large. Currently, we use an empirical value of T, but we also wish to investigate the system behavior according to T in the future.

4.4.3 Activity Decay and Routing Vector Update

The reasons why it is necessary to decay activity at each node can be explained as follows:

- When the route is not used for a long time we can assume that the route is no longer a suitable route for the current session. Therefore, the previously learned state values need to be changed to avoid the use of outdated information and allow the selection of another path until a better path for the current traffic is found. However, the selection of another path will never happen if the current activity is high. Therefore, the activity must be decreased to allow the random walk mechanism to be performed.

- As the feedback packet is sent only when the data packet arrives at the destination, it can be concluded that if no data packet arrives at the destination then the activity will never be updated. In order to recover from such situations, the activity on each node must be decayed over time.

In our protocol, given the current time is t and the most recent feedback packet arrived at t_0, we use the simple activity decay equation on the stored activity:

$$\alpha(t) = \begin{cases} \alpha(t_0) - \delta & \text{if } t - \tau \leq t_0 < t \\ \alpha(t - \tau) - \delta & \text{otherwise,} \end{cases} \tag{6}$$

where the decay constant $\delta = 0.1$ is used for the current implementation. The decay process is periodically performed over interval τ. The activity decay mechanism is performed regardless of the feedback packet arrival. Therefore, when there is no incoming feedback packet, the activity will continuously be decayed and the routing vector will be updated by using the decayed activity.

To keep the information in the routing vector consistent to the value of activity, the routing vector is always updated after there is any change of the activity value, i.e., on feedback packet arrival and activity decay.

4.4.4 Attractor Selection-based Route Recovery

In MARAS, the data packet is forwarded to the destination according to the effects of activity and noise. In addition, once the packet is forwarded to the node which does not have the previously set up routing vector for that packet's destination, a new random routing vector is established as explained in Section 4.1. According to this behavior, it can be seen that the data packet is also used for route recovery mechanism.

However, using the data packet as a route recovery packet has a drawback which is a possibly lower delivery efficiency due to the packet loss rate in the recovery process. Since the delivery efficiency is crucial in most of the communication, the random packet should travel as many hops as possible to achieve the good delivery efficiency. On the other hand, the longer path of the

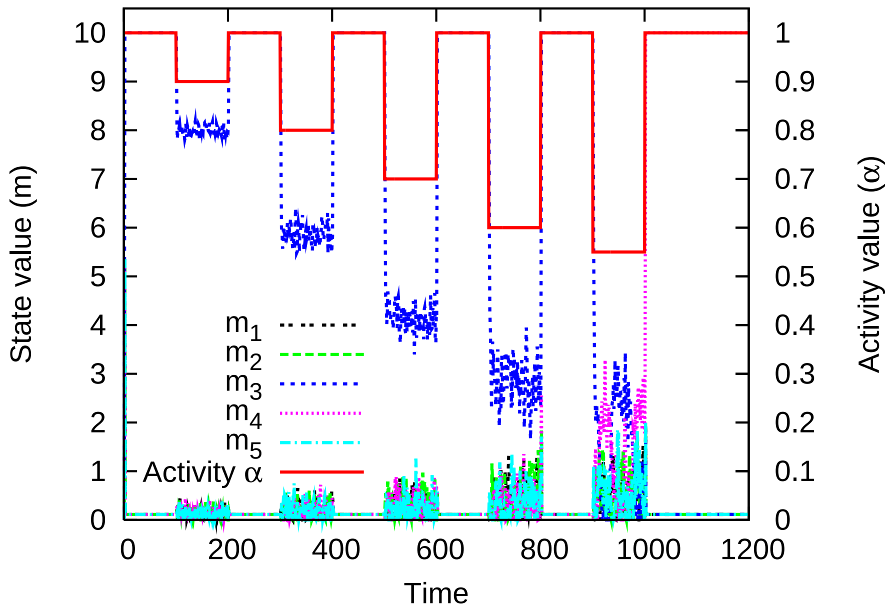


Figure 6: Maximum value switching when $\alpha < \theta$

random packet also causes the larger overhead and interference. This trade off is considered in our implementation and the *random walk range* ρ is introduced for this purpose.

First, we define the *random walk state* of a routing vector based on the relationship between the activity and the maximum state value. As shown in the Figure 6, the maximum state value is changed when the activity drops below a certain value, which we call *random walk threshold* θ. Therefore, we define that the routing vector is in the random walk state when its stored activity is below the random walk threshold, where $\theta = 0.6$ in the current implementation. When a data packet is forwarded to the destination using the routing vector in the random walk state, its TTL will be decreased to the random walk range ρ if the TTL $> \rho$, otherwise, the TTL will be decreased by one.

According to the decay function in Section 4.4.3, the activity is decayed by 0.1 every time step. The random walk threshold is set to 0.6, indirectly by tuning parameters of MARAS, to make the system to be able to tolerate to a few irregular feedback packet losses before entering the random walk state.

4.4.5 Local Connectivity Maintenance

In MARAS, the routing vector consists of the local neighbor list and the corresponding state values. When the connectivity to a neighbor node is lost, the related state value is also removed from the routing vector. As the list of neighbors plays a significant role in MARAS, the connectivity with the neighbors is maintained as long as the neighbor node is in range and remains active.

In our protocol, we adopt the HELLO packet mechanism from AODV [35] where every node periodically broadcasts the HELLO packet to notify its neighbor of its existence. When a node does not receive a HELLO packet from one of its neighbors for a certain period of time, that neighbor is considered lost and then removed from the neighbor list. With this mechanism, we can maintain the neighbor list and tolerate some transmission failures of HELLO packets. However, the explicit local route repair mechanism of AODV is not adopted in MARAS.

5 Evaluation

We evaluate MARAS by performing simulations with the discrete-event network simulator QualNet [19]. MARAS is compared to AntHocNet [14] and AODV. We use the code of AntHocNet from the developers available at [36]. The implementation of AODV in QualNet version 4.0 is based on AODV draft 8 [35] with extensions from draft 9 [37]. Three different variants of AODV, which are *AODV*, *AODV+L*, and *AODV+LI*, are used in this evaluation. First, AODV is a standard AODV configuration according to QualNet 4.0. Next, AODV+L is a standard AODV with an addition of local route repair feature. Finally, AODV+LI is a standard AODV including the local route repair feature and allowing an intermediate node to respond to a route request.

The standard AODV, which has no local route repair feature and allows only the destination to respond to a route request message, is widely used in many studies on MANET routing protocols as a reference protocol for evaluation, e.g., [8, 15, 16, 20, 30]. However, it is an unfair comparison in our case because the error recovery mechanism of the standard AODV lacks adaptability, causes high delay, and high overhead in the process. Therefore, we use these variants of AODV to study the effect of the amount of route recovery control messages. The standard AODV has to recover from end-to-end which causes the largest amount of control messages among the 3 variants. AODV+L has to recover only from the point of failure to the destination which causes less control overhead than AODV. As AODV+LI has to find only the next valid intermediate node in order to recover, it requires the least amount of control overhead for recovery among the 3 variants.

Consequently, we consider three metrics in this evaluation: delivery efficiency, transmission overhead, and average path length. First, the *delivery efficiency* is the ratio between the number of successfully delivered data packets at the destination and the number of data packets sent from the source. Next, the *transmission overhead* is the ratio of the sum of all unicast and broadcast transmissions in the network for the whole simulation over the number of the successfully delivered data packets. This metric reflects the amount of network load inflicted by the delivery of each data packet. Finally, the *average path length* is the average of the travelled hop count of successfully delivered data packets.

Table 2: Summary of simulation configurations

Parameter	**Failure Scenario**	**Mobility Scenario**
Terrain size	$1500 \times 1500\,m^2$	
Wireless module	802.11b	
Wireless data rate	2 Mbps	
Application traffic	CBR (UDP)	
Traffic data rate	8 kbps	
Traffic session	1 or 2	1, 2, or 10
Number of nodes	121, 169, or 256	256
Simulation time	1000 s	
Traffic time	0–1000 s	

5.1 Simulation Configurations

The evaluation is separated into two main scenarios: a failure scenario (see Section 5.2) and a mobility scenario (see Section 5.3). In the failure scenario, the failure model which is described in Section 5.1.4 is used. In the mobility scenario, we use the random waypoint model along with certain parameters that are described in Section 5.1.5. In this section, we describe both the common simulation configurations and the specific configurations in each scenario.

5.1.1 Terrain Size and Node Placement

The area of the evaluation scenario is $1500 \times 1500\,m^2$ for both scenarios. In the failure scenario, nodes are placed within this area using the uniform node placement tool available in QualNet. The tool divides the area into a grid with the number of tiles equal to the number of node and places the node randomly within each tile in order from the tile at lower left corner to the one at upper right corner. The number of nodes is varied from 121, 169, to 256 in the same area. The numbers of nodes are chosen to be larger than the example configuration in the evaluation of AntHocNet to prevent connectivity problems as some of the nodes will fail due to the failure model. Moreover, the effect of node density can be studied by these configurations. The node positions remain the same throughout the simulation as node movement is not considered in this failure scenario.

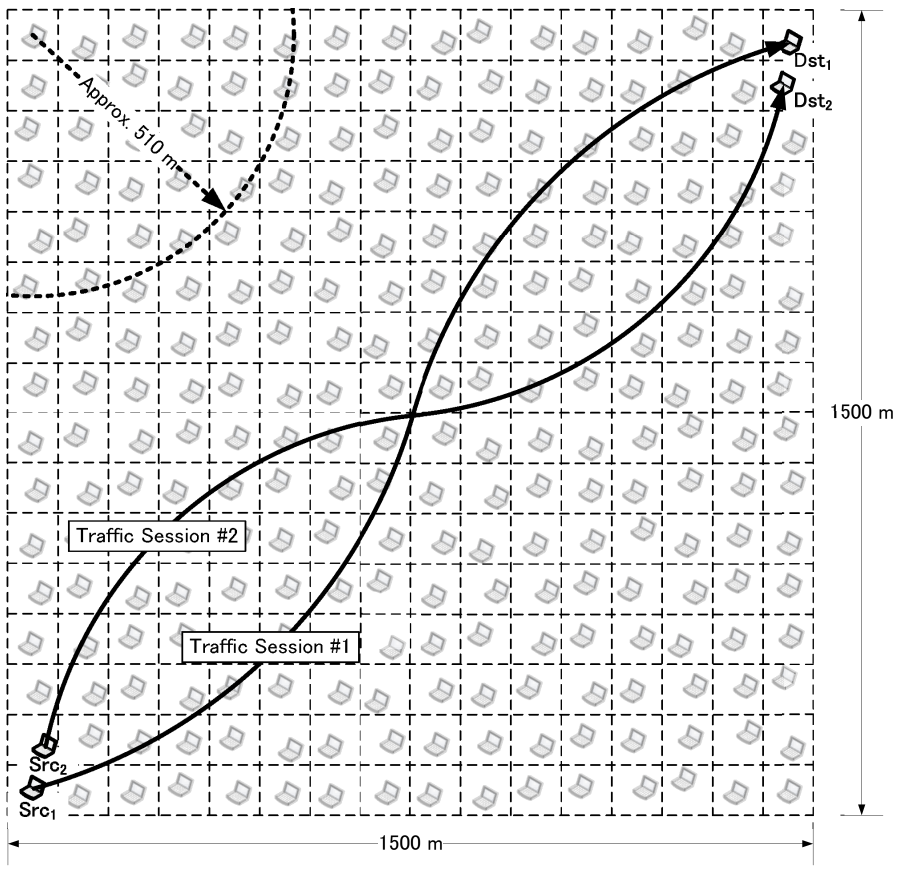


Figure 7: Example of failure scenario

Instead, we study the adaptability of our proposal by using a failure model which is described in Section 5.1.4. An example of the uniform node placement of failure scenario is shown in Figure 7.

In the mobility scenario, 256 nodes are randomly placed within the same terrain size using the random node placement tool in QualNet. The adaptability of MARAS is studied using the random waypoint mobility model which is explained in detail in Section 5.1.5. An example of random node placement and how the path from the source and the destination changes as a result of the mobility is shown in Figure 8

5.1.2 Wireless Configuration and Traffic

Each node in the simulation uses the IEEE 802.11b wireless module with data rate of 2 Mbps which is the common configuration in many protocol evaluations, e.g., AntHocNet and HOPNET.

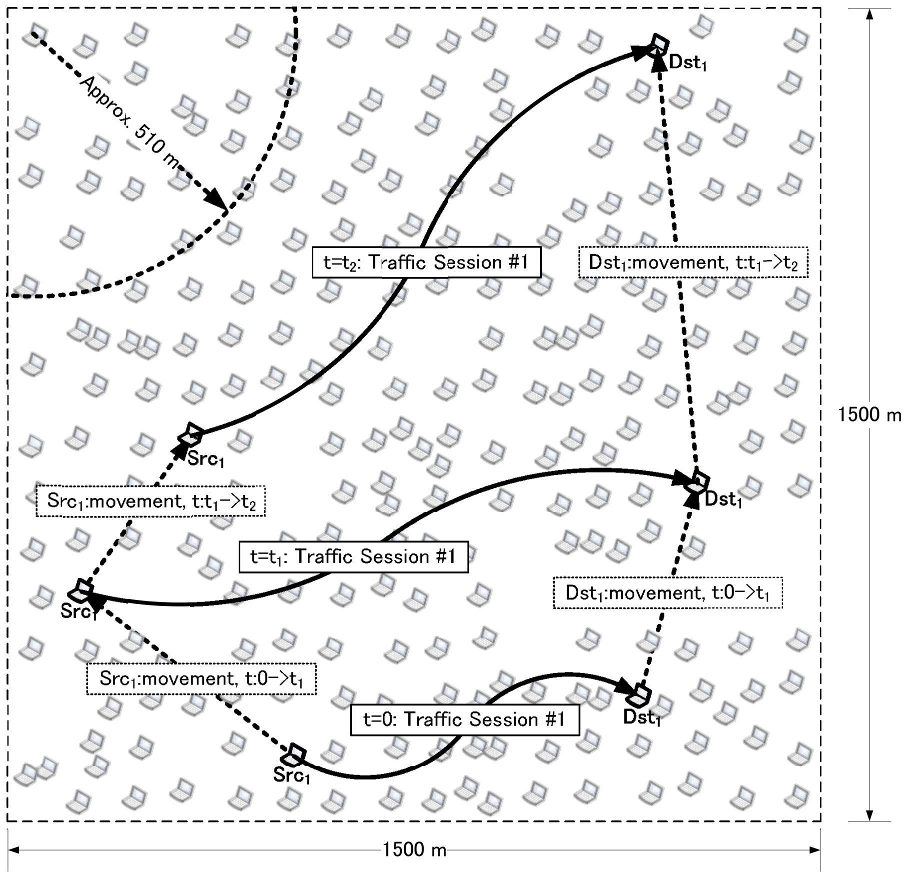


Figure 8: Example of mobility scenario

The approximate radio range is 510 m as we use QualNet's free-space model without fading. Regarding the traffic, constant bit rate (CBR) is used as an application with UDP as a transport layer protocol. In order to observe the pure performance of MARAS, we select UDP as a transport protocol to avoid effects from the congestion control mechanisms of TCP. We use CBR bit rate of 8 kbps which sends out 10 packets per second. Additionally, the wireless interface buffer at each node can store 50000 packets which can be regarded as infinite for the current traffic condition. In the both scenarios, the simulation time is 1000 s where the traffic generation starts and ends at the same time as the simulation.

5.1.3 Protocol Parameters

The specific parameters of MARAS are summarized in Table 3. Two values of random walk range ρ are used in this evaluation and the effects of random walk range ρ are discussed in Section 5.4.

Table 3: Simulation parameters of MARAS

Catagory	Parameter Name	Parameter Value
Attractor selection	High value β	10
	Activity exponent γ	3
Activity calculation	Window interval T	1.0 s
	Decay constant δ	0.1
	Decay interval τ	1.0 s
Routing	Random vector's initial value λ	0.5
	Random walk threshold θ	0.6
	Random walk range ρ	10 or 20

The parameters of AntHocNet are set according to the sample configuration file provided with the code in [36]. The other parameters of AODV and MARAS, which are not given here, are default values according to the implementations in QualNet 4.0.

5.1.4 Failure Model

In this evaluation, a failure model is used to simulate topology changes which are caused by joining and leaving nodes. We force a number of nodes to fail at the same time by switching their wireless interfaces off using the available API in QualNet. Consequently, link failures occur and the route recovery performance can be evaluated using this failure model. Failing nodes are randomly selected among all nodes in the simulation area excluding the source(s) and the destination(s).

To maintain the number of active nodes, the failure period is shortened as the number of failure occurrences is increased. In other words, when we have low number of failure occurrences, the nodes fail less frequently but have a longer failure period than in the case of more failures. Therefore, the number of failure occurrences proportionally reflects the degree of network dynamics.

The configurations of the number of failures are between 0 and 90 with the incremental step of 10 occurrences. In each failure, the numbers of failing nodes are approximately 25% of all nodes, which are 30, 42, and 64 nodes for 121, 169, and 256 nodes scenario, respectively. The failure interval is calculated by dividing the simulation time by the number of failure occurrences, which ranges between 100 s in case of 10 failures to 11.11 s in case of 90 failures. The first group of nodes starts failing at 0 s. Iteratively, the previously failing nodes recover from failures after the failure interval ends and the new group of randomly selected failing nodes starts failing. Note that the value 0 means no failure occurrences or a static scenario.

5.1.5 Mobility Model

One of the important characteristics of MANET is mobility. Therefore, MARAS is also evaluated in a mobility scenario. The random waypoint mobility model (RWP) is used in our protocol because it is the most common mobility model in the evaluations of many routing protocols. According to [38], among three random-based mobility models, RWP has been found the most suitable for AODV. In RWP, there are 3 main parameters: a maximum speed, a minimum speed, and a pause time. The mobile node under this model will select a random target and a random speed within the range of minimum and maximum speed for moving toward the target. Once the mobile node reaches the target, it will remain still at that target for *pause time* period before repeating the process again.

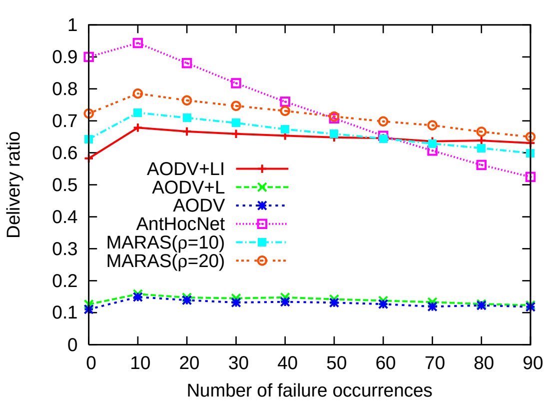
In our mobility scenario, we use 0 as a minimum speed and 2, 5, and 10 m/s are used for the maximum speed, where the average speeds roughly correspond to walking speed, running speed, and the speed of a bicycle or a scooter, respectively. Moreover, the pause time is set as 0 to study the pure effect from mobility.

5.2 Failure Scenario

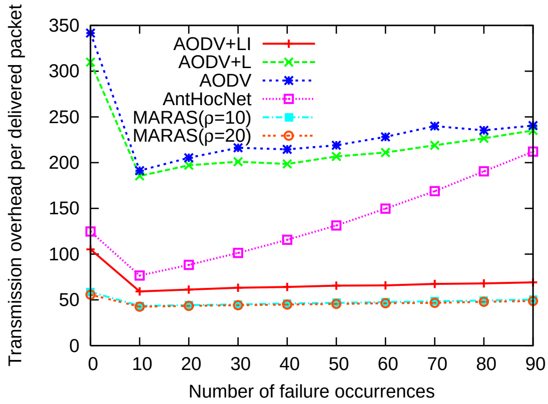
In this section, the evaluation results from the failure scenario are shown and discussed. First, MARAS is evaluated with only a single traffic session. Then, we evaluate MARAS with two traffic sessions to study the effect of traffic load. The former scenario is called the single session failure scenario and the latter is called the multiple sessions failure scenario.

5.2.1 Single Session Failure Scenario

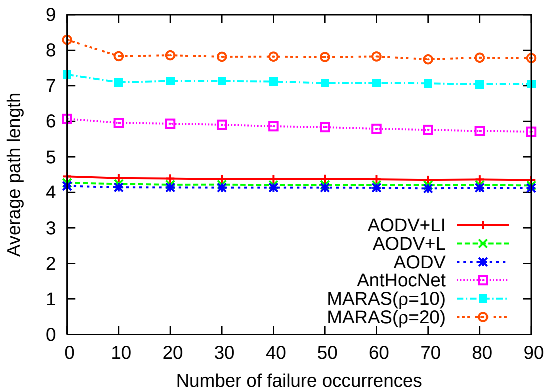
The first scenario that we investigate is the single traffic session scenario. In this scenario, we have only one source and destination pair. The source is the first node, which is positioned at the lower left corner, and the destination is the last node, which is positioned at the upper right corner



(a) Delivery efficiency



(b) Transmission overhead



(c) Average path length

Figure 9: Evaluation results against number of failure occurrences (1 session, 256 nodes)

of the scenario area (see Src1 and Dst1 in Figure 7). The results of this scenario are the average values from 100 simulation runs. The results shown in Figure 9 are from the 256 nodes scenario. However, we also show the comparison with other node density values in Figure 10.

The delivery efficiency results are shown in Figure 9(a) on the Y-axis against the number of failure occurrences on the X-axis. From Figure 9(a), it can be observed that AntHocNet has higher delivery efficiency than the other protocols in low failure occurrences cases. However, MARAS with random walk range $\rho = 20$ performs better than the other protocols once the failure occurs more often than 50 times in the whole simulation. Among the variants of AODV, AODV+LI has the highest delivery efficiency which reflects that the shorter route recovery control messages travels, the better adaptability and the better delivery efficiency are in this random failure scenario.

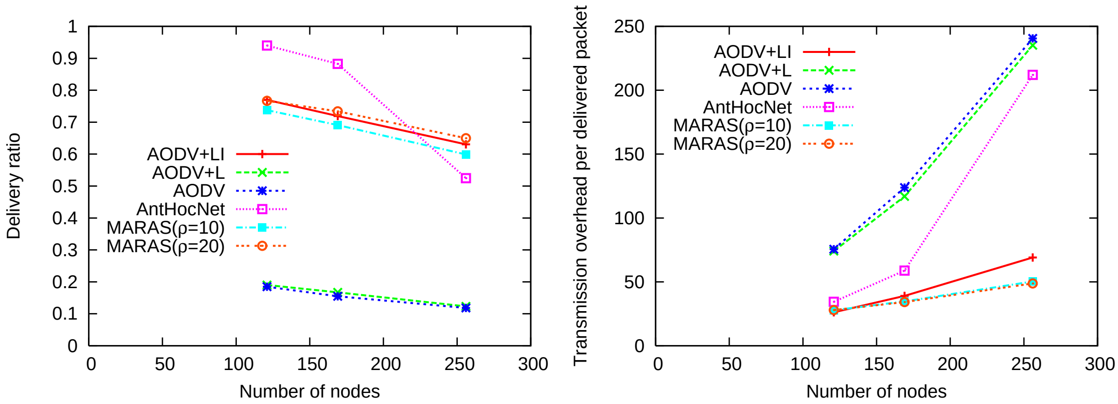
AODV+LI has a slightly higher delivery efficiency than MARAS with random walk range $\rho = 10$ in the high failure occurrences scenario because of the higher probability of packets getting dropped during random walk by the ρ-limited TTL which suppresses the exploratory behavior of MARAS. The slightly dropping tendency of delivery efficiency in the case of MARAS with random walk range $\rho = 20$ can also be explained similarly.

We define the overhead metric as the transmission overhead per successfully delivered packet. This metric indirectly indicates the network load inflicted by the routing protocol per successfully delivered packet. According to Figure 9(b), even though MARAS uses a feedback packet per every successfully delivered packet, which causes traffic to be doubled, MARAS achieves the lowest overhead among all protocol in all failure occurrences. This is the effect of the trade-off between the delivery efficiency and the overhead by using the random walk range ρ in MARAS. Moreover, the overhead of MARAS and AODV remains almost constant regardless of the number of failure occurrences while the overhead of AntHocNet has the tendency to increase with the network dynamics. It is obvious that the overhead of AntHocNet is much worse than AODV+LI and MARAS in contrast to the better delivery efficiency in this scenario.

The last metric is the average path length which is calculated by averaging travelled hop count of successfully delivered packets. Figure 9(c) shows the average path length results and MARAS has approximately 2 times longer path length than AODV and slightly longer path than AntHocNet. Normally, MARAS should cause more overhead and has lower delivery efficiency as it has a longer path. However, surprisingly, the overhead and the delivery efficiency differ from expected results. Our assumption is that, MARAS takes a longer path to avoid using the congested or unstable links which is caused by bi-directional traffic (data and feedback). This behavior is different from AODV which insists on using the shortest path.

Note that the sudden changes between $x = 0$ and $x = 10$ in every graph are caused by the different number of active nodes. As the failure model puts 25% of nodes into inactive state, there are less collisions caused by HELLO packets and less radio interference. Therefore, higher delivery efficiency, lower overhead, and shorter paths are expected in such situation.

In Figure 10, we show the results from the 90 failure occurrences scenario which the scenario with the highest level of dynamics. The delivery efficiency is shown on the Y-axis of Figure 10(a) and the overhead on the Y-axis of Figure 10(b). The X-axis is the number of nodes or node density for both figures. It can be observed that the performance of AntHocNet regarding node density



(a) Delivery efficiency with 90 failure occurrences (b) Transmission overhead with 90 failure occurrence

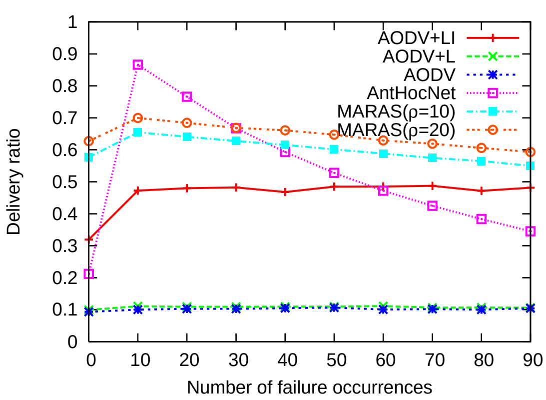
Figure 10: Evaluation results against number of nodes (1 session, 256 nodes)

drops in non-linear manner while the performance of MARAS and AODV+LI drop similarly in linear manner. Hence, we can say that MARAS and AODV+LI are more scalable than the other protocols in this scenario.

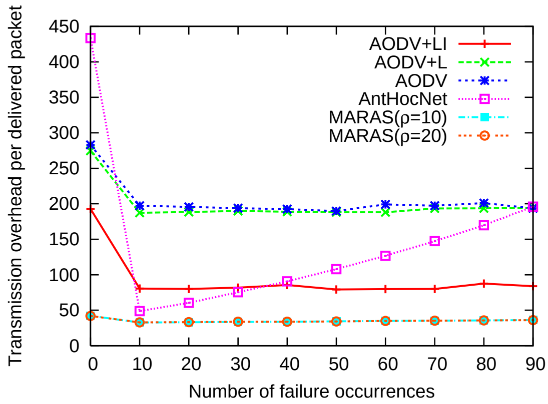
5.2.2 Multiple Sessions Failure Scenario

After we observed the average path length of MARAS, we evaluate the performance of MARAS, AODV, and AntHocNet, when the traffic load increases. This scenario has two source and destination pairs. The first pair is the same as in the single scenario while for the second pair the source is the second node and the destination is the second to last node (see Figure 7). The results are the average values of 100 simulation runs. For the simplicity of comparing the results with the single session failure scenario, all results are the averages of the two sessions in this scenario.

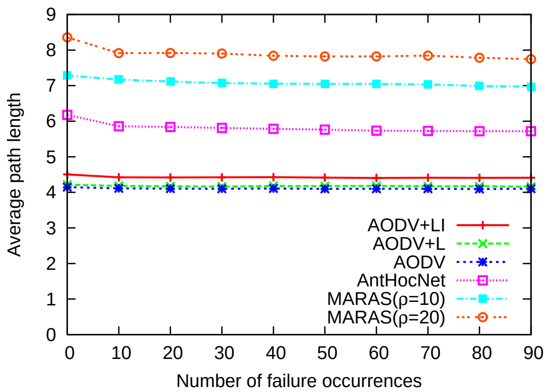
In Figure 11, similar results to the single session failure scenario can be seen. While the average path length of MARAS in Figure 11(c) is still approximately 2 times longer than AODV, MARAS has higher delivery efficiency and lower transmission overhead per successfully delivered packet in all cases. Moreover, the performance gap between MARAS and AODV increases, which shows that MARAS can handle a higher amount of traffic than AODV before the performance degrades. When comparing the Figure 11(a) and Figure 9(a), the delivery efficiency of MARAS drops only approximately 5–10%, but the delivery efficiency of AODV drops 10–15%. Regarding AntHocNet, even though the delivery efficiency is still higher for low failures, it becomes much



(a) Delivery efficiency with 256 nodes



(b) Tranmission overhead with 256 nodes

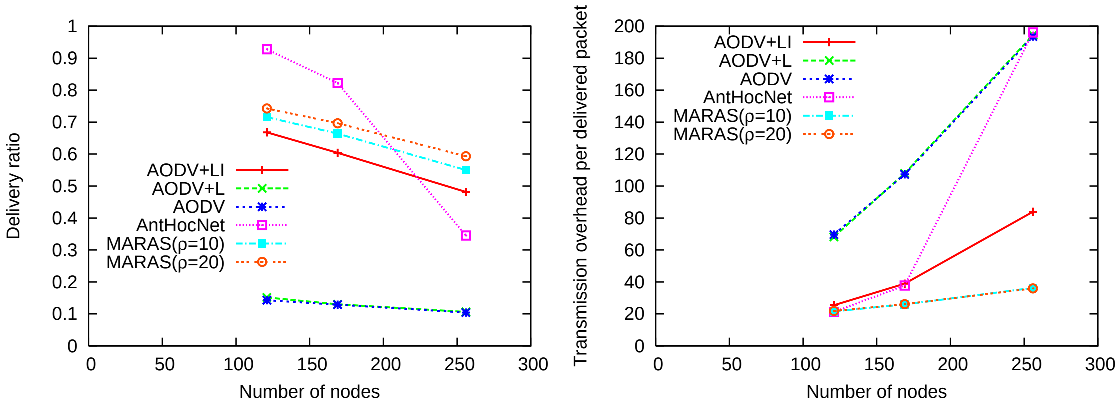


(c) Average path length with 256 nodes

Figure 11: Evaluation results against number of failure occurrences (2 sessions, 256 nodes)

lower and drops faster over the number of failure occurrences. Moreover, the tendency of overhead is still the same as in Figure 9(b) which is much worse than AODV+LI and MARAS. Another interesting behavior to point out is the increasing overhead of AODV+LI. Comparing to Figure 9(b), it can be observed that the overhead of AODV+LI in Figure 11(b) becomes almost double, which is in proportion to the increased amount of traffic.

Similar to Figure 10 in the single session failure scenario, we show the results from the 90 failure occurrences scenario which the scenario with the highest level of dynamics in Figure 12. In this figure, a similar conclusion as in the single session failure scenario can be made. Not only does MARAS have higher performance regarding node density than AntHocNet, but also the performance gap between MARAS and AODV becomes larger. In Figure 12(b), the over-



(a) Delivery efficiency with 90 failure occurrences (b) Transmission overhead with 90 failure occurrences

Figure 12: Evaluation results against number of nodes (2 sessions, 256 nodes)

head of AODV+LI with respect to the node density increases faster than MARAS. Moreover, it also increases faster than the result in Figure 10(b), while MARAS still maintains the same tendency in both scenarios. Therefore, it is confirmed that MARAS is more scalable than AODV and AntHocNet in this scenario.

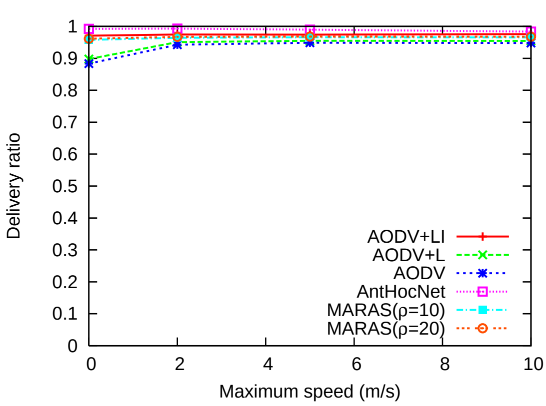
5.3 Mobility Scenario

In this section, the evaluation results from the mobility scenario are shown and discussed. In the mobility scenario, the node placement and the selection of the source and destination pair(s) are random (see Figure 8). The evaluation results shown in this section is are the average values from 100 simulation runs. The evaluation is also performed in two scenarios: a single session mobility scenario and a multiple sessions mobility scenario.

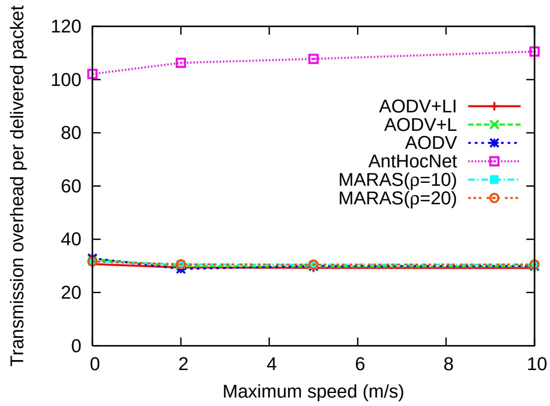
5.3.1 Single Session Mobility Scenario

In this scenario, there are 256 nodes, randomly placed in the $1500 \times 1500\,\mathrm{m}^2$ area and there is only one randomly selected source and destination pair among 256 nodes.

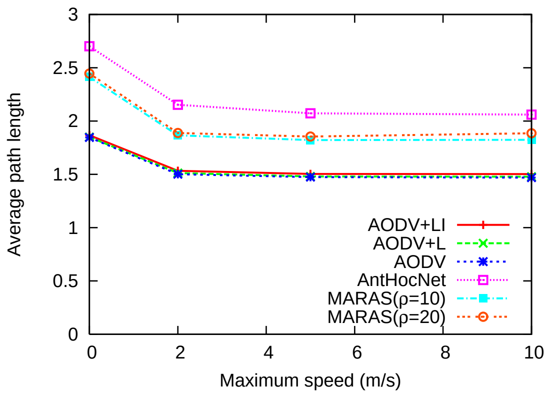
The delivery efficiency results are shown in Figure 13(a). The X-axis of the three figures shows the maximum speed. It can be observed that there is not much difference in the delivery efficiency and the path length for all protocols. However, the overhead of AntHocNet is very high compared to MARAS and AODV in Figure 13(b). Note that, the improvement of the delivery efficiency over



(a) Delivery efficiency



(b) Transmission overhead



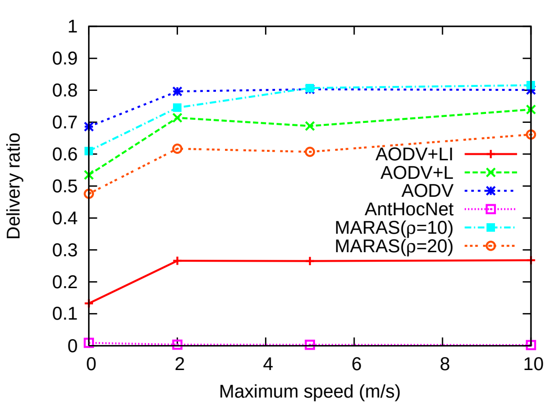
(c) Average path length

Figure 13: Evaluation results against maximum speed (1 session, 256 nodes)

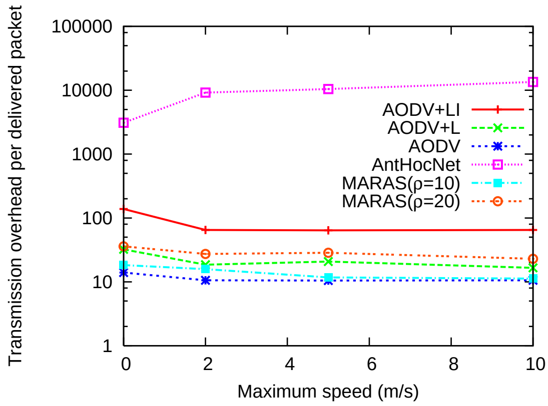
that in the failure scenario results can be considered as the effect of having shorter average path length from the random node placement and the random selection of the source and destination pair, comparing Figure 13(c) to Figures 9(c) and 11(c).

5.3.2 Multiple Sessions Mobility Scenario

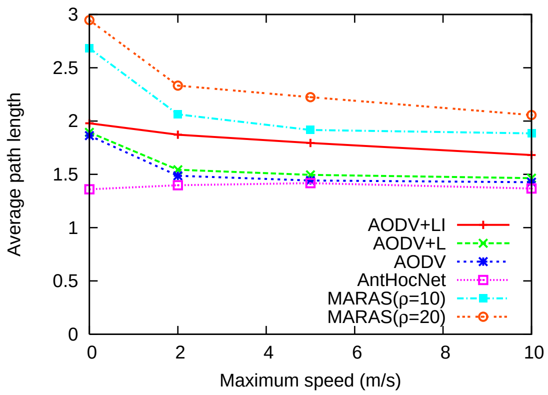
In the multiple sessions mobility scenario, we have more than one concurrent traffic session in the network. In this evaluation, 2 and 10 concurrent traffic sessions were performed but only the results for 10 concurrent sessions are shown here as they are more significant. Similar to the single session mobility scenario, the source and the destination pairs are selected randomly among 256 nodes. However, each node can be either the source or the destination for only one traffic session



(a) Delivery efficiency



(b) Transmission overhead



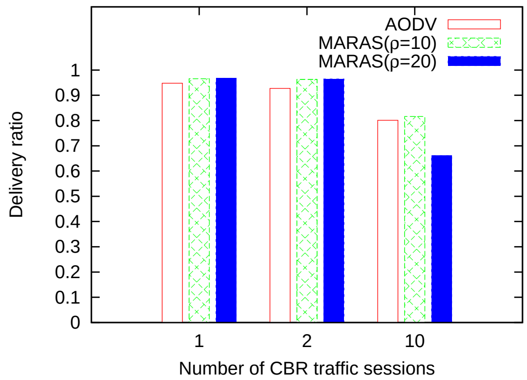
(c) Average path length

Figure 14: Evaluation results against maximum speed (10 sessions, 256 nodes)

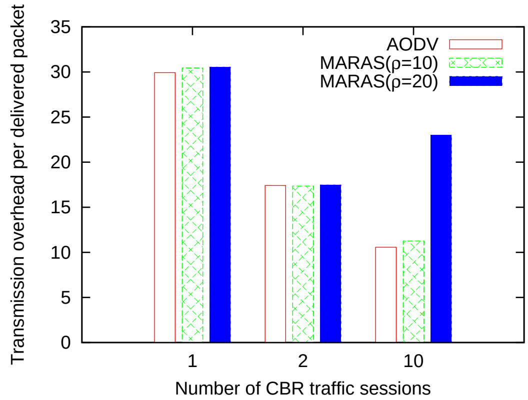
to avoid a bottleneck problem.

The delivery efficiency results are shown in Figure 14(a). First, the delivery efficiency of AntHocNet totally deteriorates in this high traffic load scenario. The reason is quite obvious that AntHocNet requires very high overhead as seen in the failure scenarios and the single session mobility scenario of the mobility scenario. Consequently, the loss of control packets is high as the network is congested with the high level of traffic and AntHocNet cannot perform well in such situation.

Next, the delivery efficiencies of AODV and AODV+L become much better than in the cases of the failure scenarios. In contrast, the delivery efficiency of AODV+LI becomes worse. AODV+LI shows the tendency of degrading performance when the traffic load is increased in the failure sce-



(a) Delivery efficiency



(b) Transmission overhead

Figure 15: Effects of random walk range ρ in mobility scenarios (maximum speed = 10 m/s)

narios and this result supports that tendency. Unlike AODV+LI, route recovery packets are flooded from the source in AODV and AODV+L. This mechanism can find the shorter path, according to the results in Figure 14(c), than flooding the route recovery packets from the point that the link failure occurs in AODV+LI. As a result, AODV and AODV+L have higher delivery efficiency than AODV+LI. Comparing AODV and AODV+L, it can be observed that AODV performs better than AODV+L which means that the correctness of routing information at the intermediate nodes is not good enough and it is better to let only the destination respond to the route request packet in this mobility scenario.

Comparing MARAS to AODV, the delivery efficiency of AODV is slightly larger in the scenarios where the maximum speed is less than 5 m/s, but MARAS with $\rho = 10$ has slightly higher delivery efficiency when the maximum speed becomes larger. However, these differences in terms of both delivery efficiency and overhead between MARAS and AODV are not significant and it can be concluded that MARAS with $\rho = 10$ has approximately the same level of performance as AODV in this scenario.

5.4 Discussion on Random Walk Range (ρ) Parameter in MARAS

When the the random walk range ρ becomes larger, the random walk packets take longer time to travel in the network and cause more overhead than lower values of ρ. Therefore, the overhead of MARAS with $\rho = 20$ has higher overhead than MARAS with $\rho = 10$ as shown in the case of

10 traffic sessions in Figure 15(b). Due to the effect of this overhead, the delivery efficiency of MARAS with $\rho = 20$ becomes slightly lower than AODV and MARAS with $\rho = 10$, which can be seen in Figure 15(a). However, the negative effects from this behavior cannot be seen in the low number of traffic sessions nor in the failure scenarios. The cause for this effect still requires further investigation in the future.

5.5 Discussion on Adaptability

In this section, we provide a discussion related to the adaptability of MARAS comparing to the other protocols: AntHocNet and AODV. First of all, we aim at designing MARAS as a general purpose routing protocol for MANETs. Therefore, we would like to clarify that MARAS is an adaptive routing protocol in accordance with its purpose in this section.

Both of the reference protocols: AntHocNet and AODV, can be tuned up as special purpose routing protocols with high efficiency according to the evaluation in their proposals. In [39], there are many parameters that have effects on the protocol's behavior and performance. Even though the previously tuned parameters of AntHocNet are suitable for scenarios in their evaluation, using the same set of parameters on our scenario gives different results. In our case, AntHocNet has higher delivery efficiency than AODV and MARAS only when the level of network dynamics and the level of traffic are low. However, tuning the AntHocNet to be suitable for a certain network configuration requires a lot of efforts and also depends on the user's application which is unknown and may also change over time. In short, AntHocNet does not hold the adaptability that we seek to have in MARAS.

On the other hand, AODV has many features that can be selected to match the characteristic of the network and the application that it will serve under. In our evaluation: AODV, AODV+L, and AODV+LI are used. AODV+LI performs well in the failure scenarios, but worse in the mobility scenarios. In contrast, AODV does not performs well in the failure scenarios, but performs very well in the mobility scenarios. In this case, AODV is better than AntHocNet in terms of adaptability which is our main objective. However, it still requires little modifications on deployment as well as the selection of the appropriate variant of AODV depending on the situation..

In various scenarios, MARAS might not have shown the best delivery efficiency or the lowest overhead among all evaluated protocols, but it can maintain relatively high performance. It can be applied to every scenario in our evaluation with sufficiently high performance without changing any parameters. Moreover, the current parameters we used for MARAS are chosen empirically and may not even be the optimal ones. Therefore, it may be possible to further improve the performance of MARAS by exhaustively studying the impact of all parameters, e.g. ρ, β, γ. In other words, it can adapt to various network characteristics, various levels of traffic, etc. Therefore, it can be concluded that MARAS is an adaptive general purpose routing protocol for MANETs.

6 Conclusion and Future Work

In this thesis, we present MARAS, an biologically-inspired and adaptive routing protocol for MANETs. For each node operating with this protocol, a next hop selection is performed using the attractor selection mechanism. This mechanism is inspired from cell biology from which it inherits the ability to react to a continuously changing environment. The attractor selection mechanism is formulated by nonlinear stochastic differential equations with a control factor, called activity, which controls the influence of randomness in the selection process. This protocol reactively establishes the route between the source and the destination and maintains it by using feedback packets for each successfully delivered packet at the destination. The feedback packet evaluates the route that the data packet has taken and updates the activity at each node in the route by using the hop count information, allowing the route to react to changes in the network, e.g., node failures and mobility, without creating additional control overhead on changes. As a result, MARAS achieves a higher delivery efficiency and a lower overhead than other well-studied MANET routing protocols, AODV and AntHocNet, because of its adaptability to frequent failures. Moreover, when the node density increases, the overhead of MARAS remains almost constant and the delivery efficiency decreases slower than AODV by which we conclude that MARAS is more scalable. Additionally, MARAS is capable of maintaining its performance throughout all the evaluated scenarios in this study without the need of fine-tuning the parameters to adapt to new conditions as in other protocols. Therefore, it is concluded that MARAS is suitable as an adaptive general purpose routing protocol for MANETs.

In the evaluation, a lower overhead of MARAS has been observed in spite of the longer path, leading to the assumption that the stochastic behavior of MARAS might be capable of avoiding the congested and unstable links in contrast to the persistent routing based only on the shortest paths in AODV. As future work, we are interested in studying if MARAS is suitable not only for route selection but also the traffic management functionality. Moreover, we would like to investigate the effects of parameters of MARAS, i.e., ρ, β, and γ, to be able to fine-tune the performance of MARAS. We expect that once the influences of the parameters on the behavior of MARAS have been well studied, we can even further improve the performance of MARAS for specific applications or environments in addition to its general purpose adaptability.

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