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Title

Subtitle (optionl)

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...thanks to...

Contents

Summary

...summary....

Minimum Route Advertisement Interval (MRAI)

1 Introduction

- How is internet built
- the protocol that controls internet

1.1 Internet nowadays

- Use today studies to show how internet is today

1.2 Correlation between variables and convergence

- Expose the hypothesis of the correlation

Forget about the possibility to converge in seconds or even sub-seconds when we talk about internet routing convergence there are a lot of factors that influence it. The convergence time is mostly affected by some timers that rules the Internet. It could require up to different minutes to achieve a complete convergence, spread a new routing information to all the nodes.

One of the most effective timers is MRAI and it has been already proven FiXme: Insert citation that whith

1.3 Goal of this thesis

- Why is important understand this correlation?

2 BGP state of the art

- BGP de facto standard on the internet
- What is an AS
- interconnection between ASes

2.1 BGP

- High level of BGP
- BGP messages
- BGP Update messages
- BGP policies

2.2 BGP Wedgies

- What are wedgies?
- why are them important?
- which situations them occur?

2.3 BGP MRAI

- What is MRAI?
- Previous works on MRAI
- Suppositions on the MRAI influence

2.4 BGP RFD

- What is RFD?
- Why is used RFD?
- Evolution of RFD?
- RFD Today

3 Discrete Event Simulator

Experiments on Border Gateway Protocol (BGP) are not applicable on the Internet, for this reason different studies shows their results using a simulate environment [1] FiXme: Insert other citations. The majority of the studies uses small graphs, and each node of the graph simulate the behaviour of a BGP speaker. Each node represent also a single Autonomous System (AS) and the BGP speaker is it's own exterior router, for simplicity reduced to one speaker that handles all the connections.

For this reason I decided to use and expand a Discrete Event Simulator (DES) that permits to have different grades of freedom, respecting on the other side all the properties required for a reliable simulator environment. I decided to use the *Simpy*[1] package to make the environment evolve. I decided for this package for the extensive documentation and because it has been already used for different studies, demonstrating its adaptability [2, 3].

I developed the DES as a highly modular environment. In Figure 3.1 is possible to see the basic

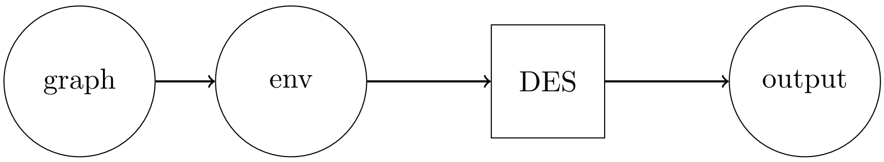


Figure 3.1: Discrete event simulator structure

idea of the simulator. The first component needed is a graph, represented by a *graphml* file, this file is descriptor of the network. it defines also all topological information and all the properties of each single node. FiXme: Look for a Cref implementation of this In Code 3.1 is possible to see an example of a *graphml* file, it describes that node 0 contains a single destination and that the edge between nodes 2 and 5 is controlled by the policy —2, 2, 2— that defines a servicer-provider policy. Policies are encoded using the convention described in [4].

```
<node id="0">
     <data key="d0">10.0.0.0/24</data>
</node>
<edge source="2" target="5">
    <data key="d2">2, 2, 2</data>
</edge>
```

Code 3.1: Graph example

The graph is then embedded in the environment file, this file is in *json* format and it describes how the environment is characterized, it gives the initial values for the Random Number Generator (RNG) so that each experiment is replicable and other properties, like where the output should be saved, and, most importantly how the experiment should be conducted. There are two possible evolution of the environment:

- ***Continuous evolution***: In this category all the nodes that contains at least a destination will continuously share and retrieve the destination accordingly with the distributions defined in the environment;
- ***Signaling evolution***: Is possible to define a precise signal that should be executed by the nodes that contains a destination, for example, the signal "AWA" defines that there will be an announce followed by a withdraw and the an other announce.

[1] Simpy website

The DES take as input this *json* file where all the information are described, it creates an object for each node in the graph file, with each own characteristics. After the initialization all the nodes that contains a destination will schedule the first advertisement of it to their neighbour. The simulation run will terminate only if there are no more events scheduled or if the maximum simulation time is reached.

The DES will then produce a *CSV* output, with all the events that can be analyzed to see the evolution of a specific node or to evaluate the whole network.

3.1 DES Environments

Thanks to the environment codification in a *json* file is possible to define experiments with a high grade of freedom. Is possible to define multiple delays as probability functions vectors that will provide multiple runs possibility. For example, if we have 5 different possible seeds and 3 different delays, the total number of runs combinations is 15, as showed in Code 3.2. is possible to run one of the possible combination of parameters through the identifier of the single run.

```
"simulation" : {
    // seed(s) to initialize RNG
    "seed" : [0, 1, 2, 3, 4],
    ....
    // Multiple withdraw distributions
    "withdraw_dist": [{"distribution": "unif", "min": 5, "max": 10, "int": \
   0.1},
                      {"distribution": "unif", "min": 8, "max": 10, "int": \
   0.1},
                      {"distribution": "unif", "min": 2, "max": 3, "int": \
   0.1}],
    ....
}
```

Code 3.2: Environment example

In the environment is possible to define also the processing time, this time is used inside each BGP node to emulate the processing of information or the evaluation of a packet. Though the *delay* parameter is possible to define the default delay on the edges, is important to remember that the links are FIFO so there is no reordering of messages in the same link, there is also no messages lost. That because it was out of the scope of this thesis to study the evolution of the protocol with packet loss, but it could be a future work.

3.1.1 Clique environment

One of the special environment that I used it's composed by a clique graph graph of different dimensions, an example of clique graph is given in Figure 3.2.

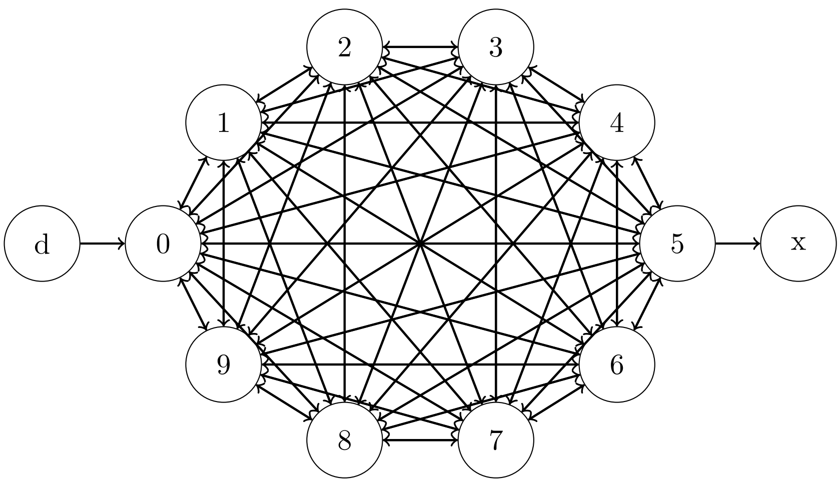


Figure 3.2: Clique graph example

The only node that shares a destination is the node "d", the node 0 will then spread the knowledge to the whole network, and the node "x" will act as a black hole for all the possible paths that the node 5 will share. This topology is used to enforce the path exploration problem.

3.1.2 Fabrikant environment

Another interesting chase to test the path exploration problem is the one presented in [5]. In that study Fabrikant et al. presents how particular MRAI setting could make the network converge with an exponential bechaviour because of the path exploration problem. I used the basic example of their study to investigate how the choose of MRAI is foundamental for the network convergence. An example of the network used is presented in Figure 3.3.

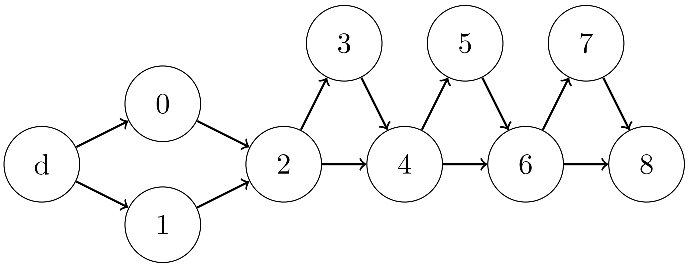


Figure 3.3: Fabrikant chain graph example

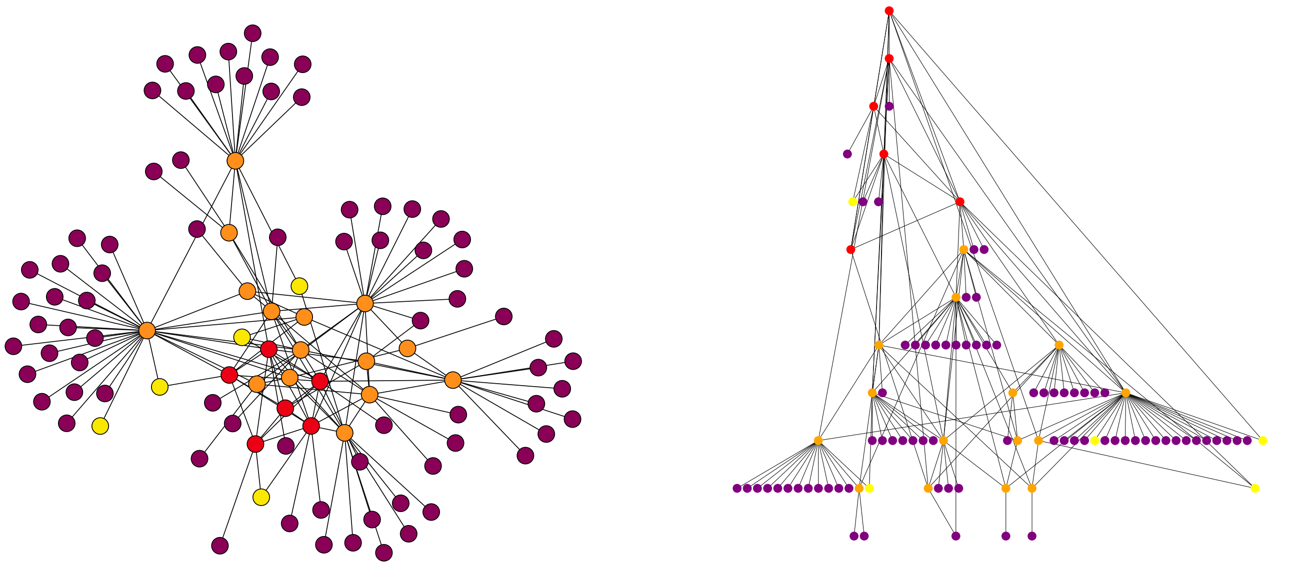
The path exploration problem is caused by the delay on the node 0-2 edge. The node 2 will receive the destination through node 1, after a small ammount of time the network will converge to the best path (without using the backup links). But, after a while, node 2 will receive the network also through node 0 and it will prefer this new path, provoking then the riconfiguration of all the other nodes that will use the backup links for a while, announcing their new path. A wrong configuration of MRAI can provoke the entire exploration of the possibility set.

3.1.3 Internet-like environment

The last noteworthy environment is the one whose purpose is to simulate Internet behaviour. This has been possible thanks to the study by Elmokashfi et al. [6] and the internet like graph generator present in Networkx[2] (a python library famous for graph and network studies). An example with a small set of nodes is presented in Figure 3.4

The different nodes are colored accordingly with the node type represented. The tier one nodes that generate the centrali clique are colored in red, and is possible to notice in Figure 3.4b that them are in the highest levels of the networks. This environment has been used to study the behaviour of the network with topologies resempbling the real internet.

[2]Networkx internet as graph generator



(a) Internet like graph with an "explosive" layout

(b) Internet like graph with a "hierarchical" layout

Figure 3.4: Internet like graph colored to show the hierarchicaly structure, 4 tipes of nodes, T (tier 1 mesh), M, CP, C (Customers, purple one)

4 Protocols as a Finite State Machine

A Finite State Machine (FSM) could be useful for a lot of purposes, to debug the protocol, to understand what is happening, to analyze leeks. It has been already done for a lot of protocols FiXme: insert citations, but not for BGP.

FiXme: Give more examples on what a protocol FSM is useful for

4.1 BGP generalization

The main idea behind the BGP FSM is to represent the knowledge as states and different set of messages as transitions. The knowledge is represented by the actual routes that the node knows to reach a single destination. Transitions encode the messages that a node has received to change state, on the edges are also inserted the response messages that the node will transmit.

FiXme: Insert image and table for an example

In BGP messages transmit information about routes, there could be the advertisement or the withdraw of the route.

Thanks to MRAI the evaluation of multiple messages could be delayed and provoke then the compression of them. For this reason on the edges we can see multiple messages, for example "A1W1A1", that will be compressed in "A1" and then evaluated.

The concept for a BGP FSM has been "taken" from [7].

- BGP as an FSM main idea
- signaling transmutation

4.2 BGP FSM experiments

The first experiments, about the translation of a single node evolution in a FSM, goal is to reproduce what has been showed in [7]. The graph used for the study is presented in Fig. 4.1.

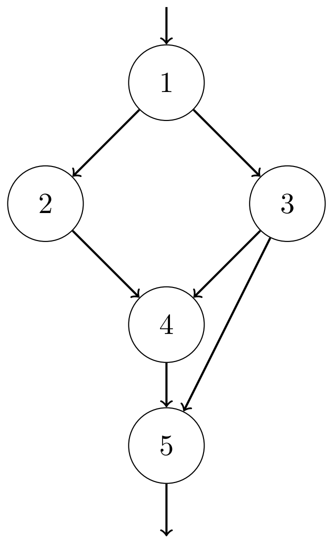


Figure 4.1: Graph from fig 4 of [7] used to study the FSM of the nodes

This topology, Figure 4.1, present an Stable Paths Problem (SPP) with five nodes [8]. The SPP model is used to eliminate much of the complexity of BGP. The arrows in the graph represent the flow of information, node 1 is the one that will receive a new route to reach an ipothetic destination and it will spread this information thourgh an advertisement (ADV) to all it neighbours. The translation to the Communicating Finite-State Machine (CFSM) will use an enumeration to encode all the paths that a single node will encounter, for example the path "5 3 1" will be converted in *a3*, each path has its own identifier. In case of withdraw the route will be encoded as *w3*.

The properties of the environment for this experiment are listed in Table 4.1.

Property	Value
Seeds	$[1, 50]$
Signaling	"AW"
Withdraws delay	Uniform distribution between 20 s and 30 s
Announcement delay	Uniform distribution between 20 s and 30 s
MRAI	0 s for every link
Link delay	Uniform distribution between 0.001 s adn 1 s, uniform distribution between 0.012 s and 3 s

Table 4.1: FSM example environment properties

The total number of runs generated by this environment is 100.

FiXme: this paragraph is cumbersome The two nodes of more itnerest are node 4 and node 4. The first one can receive multiple combination of messages from node 2 and 3, for sure there will be two announcements and two withdraws, because node 1 has to respect a predefined signaling. but, those messages could be reordered in different ways, and for each sequence of them we can encounter a different sequence of output messages thorugh node 5. Giving that the routes from node 2 and 3 will have respectively as ID 2, 3 the table Table 4.2 All possible inputs of node 4 are the shuffle of all possible outputs of nodes 2 and 3 preserving the local order.

Input signal	Output signal
$a2a3w2w3$	$a4w4$
$a2a3w3w2$	$a4w4$
$a3a2w2w3$	$a5a4a5w5$
$a3a2w3w2$	$a5a4w4$
$a2w2a3w3$	$a4w4a5w5$
$a3w3a2w2$	$a5w5a4w4$

Table 4.2: Node 4 different possible inputs and output

The node 5 will receive all the possible outputs from node 3 and 4 increasing the number of possible signals from 6 of node 4 up to 71 but some of them produce the same output signal, so we have in total 52 unique output signals from node 5.

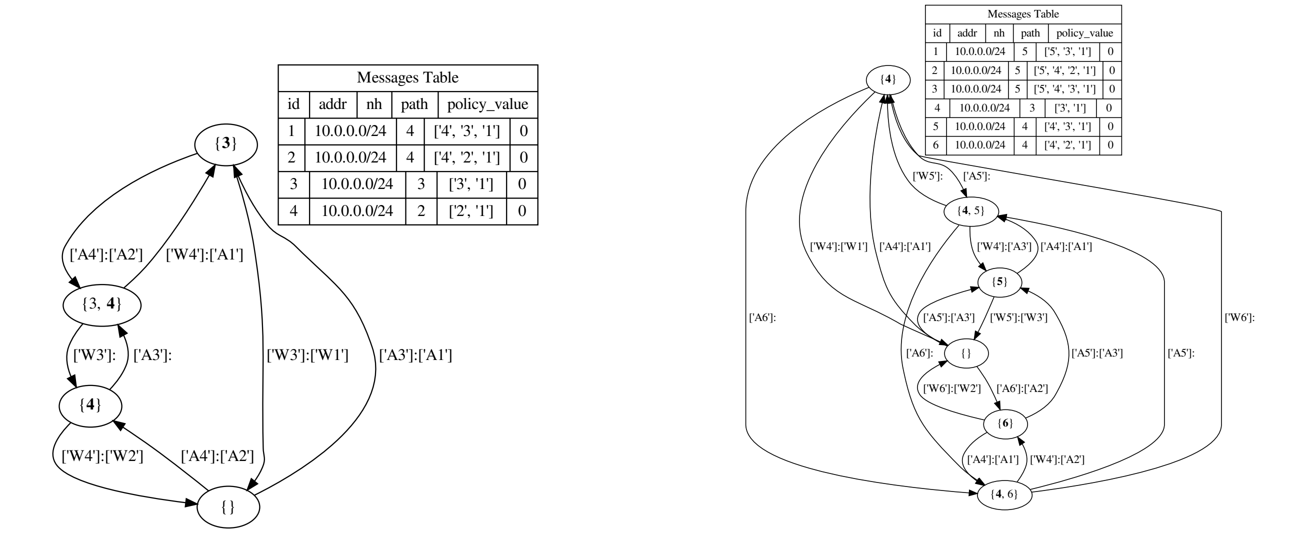
From the 100 total runs we can generate the CFSM of node 4 and node 5, in order to be able to study how the nodes reacts to different input signals. The two CFSM are presented in Figure 4.2.

FiXme: Remove message table from Figure 4.2?

The states of the CFSM in Figure 4.2 are represented by the knowledge of the nodes, composed by the routes that are in the Routing Information Base (RIB) of the node. The bold value is the actual best route to the destination chosen by the node. If in the state transition to a new state the best path is not affected then the node will not transmit the new route to it's neighbours, for an example take a look to Figure 4.2a from the state $\{1\}$ to the state $\{1, 3\}$ where the node 4 will learn a new route that is not the best one.

The effects of the implicit withdraw can be see in Figure 4.2b the transition from $\{1, 4\}$ to $\{1, 3\}$ thanks to the reception of the announcement $a3$ from the node 4.

As written in [7], I would like to underline the fact that, given the 52 unique possible outputs of the node 5 it would be very difficult to infer the initial signal that provoke all the transitions.

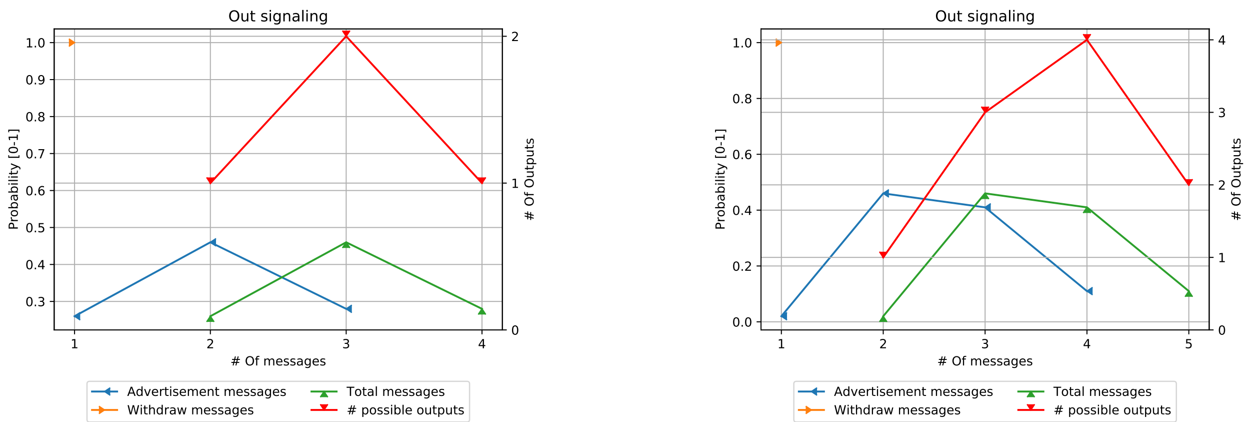


(a) Node 4 CFSM from the environment of Table 4.1

(b) Node 5 CFSM from the environment of Table 4.1

Figure 4.2: CFSM of nodes 4 and 5 of the graph Figure 4.1 with an input signal of "AW"

We can also analyze those output signals, having all the events for each single run we can infer which were the most common output signals that a signle node experienced. Is sufficent to take all the transmitted messages of a node and look the sequence of advertisement and withdraws.



(a) Node 4 output signals study

(b) Node 5 output signals study

Figure 4.3: Output signal study of nodes 4 and 5 of the graph Figure 4.1 with an input signal of "AW" at node 1

The plots in Figure 4.3 represents the probability of an output signal of a certain length to appear and the number of unique output signals of a unique length has been found. The x axis represent the number of messages in the output signal, a message is a single announcement or withdraw. The first y axis represent the probability to see a certain number of messages taking a random output signal from the output. For this axis there are three liness that refers to it, the blue one represent the number of advertisement messages in the output signal correlated with the respective probability. For example in Figure 4.3a there is a probability around 0.45 to have exactly two advertisement messages per output signal. And respectively a probability slightly larger than 0.25 to have only one advertisement or three. We can also notice that we didn't see more than three advertisements or less than one. The green line instead represent the total number of messages in the signal, without distinguishing between advertisement and withdraws. By the fact that we will always have one withdraw (the orange line) this line is simply shifted by one unit in respect of the advertisement line. The second y axis refers to the number of unique output signals encountered and their length. For example, in Figure 4.3b we will have 1 unique output signal of length 2, 3 signals of length 3 and 4 of length 4 and 2 of length 5.

Those plots does not give a compleate prospective of all the possible outputs that can be generted but only the ones encountered during the runs. Infact during the 100 runs we encountered only the output signals listed in Table 4.3.

Signal	Frequency
$a1a2a1w1$	28
$a2a1w1$	23
$a2w2$	26
$a1a2w2$	23

(a) Node 4 output signals encountered

Signal	Frequency
$a1a2a3w3$	15
$a1a3w3$	16
$a2a1a2w2$	19
$a1a2w2$	28
$a1w1$	2
$a2a1a3w3$	6
$a2a1a2a3w3$	8
$a3a1a2a3w3$	3
$a2a1w1$	2
$a3a1a3w3$	1

(b) Node 5 output signals encountered

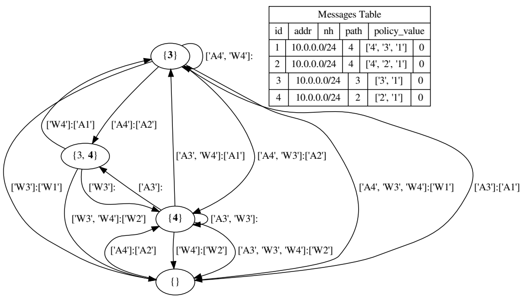
Table 4.3: Node 4 and 5 different output signals encountered during the runs

4.2.1 MRAI and BGP FSM

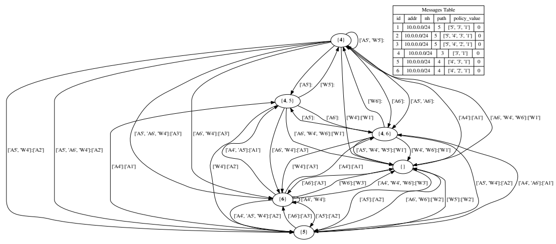
How would MRAI affect the study of the signals produced by Figure 4.1? The answer is that the number of states will be the same but the number of possible transitions will explode, thats because there will be a lot of more possible input signals that will be compressed and evaluated by the nodes.

We can see the effects of MRAI on the CFSMs in Figure 4.4.

FiXme: Figure 4.4b is not readable at all, move the two figure one after the other



(a) Node 4 CFSM from the environment of Table 4.1 with MRAI=30 s



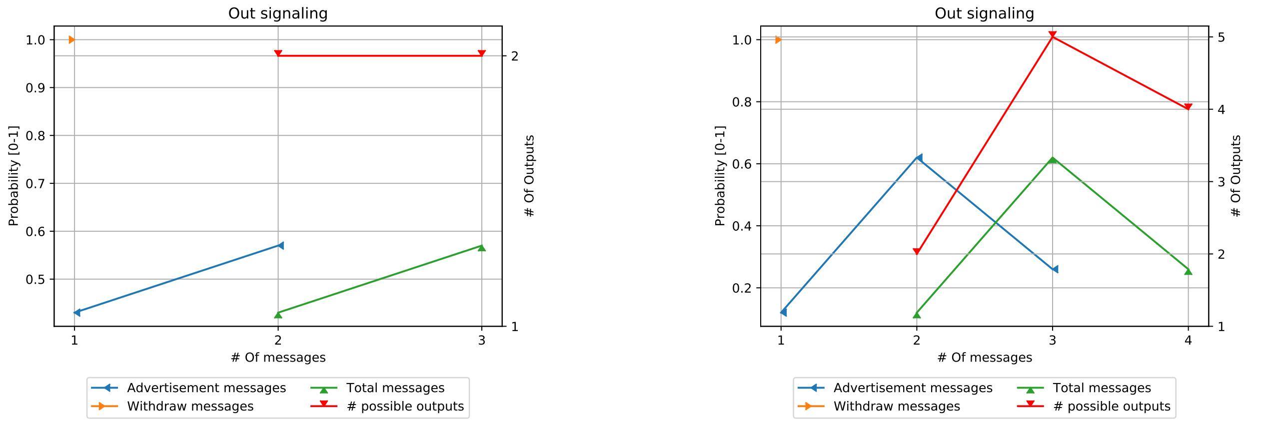
(b) Node 5 CFSM from the environment of Table 4.1 with MRAI=30 s

Figure 4.4: CFSM of nodes 4 and 5 of the graph Figure 4.1 with an input signal of “AW” with MRAI=30 s

Figure 4.2a and Figure 4.4a permits us to compare the two CFSMs of node 4 and is possible to nice a big difference in terms of edges between one figure and the other, the first one has 8 transitions, the second one 15. For the node 5 we pass from 16 transitions to 36.

But the positive effects of MRAI can be found in the output signals, showed in Figure 4.5.

Comparing Figures 4.3b and 4.5b is possible to notice that there is a different distribution of output signals. The x axis never reach the value of 5, this means that the output signals of the node 5 never used more than 4 messages. And we can also notice that the majority of the signals this time have a length of 3 messages, instead of the previous 4. This is a hint that MRAI can have positive effects on the number of utput messages produced by single nodes, having, however, more possible transitions to consider.



(a) Node 4 output signals study with MRAI=30 s

(b) Node 5 output signals study with MRAI=30 s

Figure 4.5: Output signal study of nodes 4 and 5 of the graph Figure 4.1 with an input signal of "AW" at node 1 with MRAI=30 s for every link

4.3 BGP FSM explosion

We know that MRAI is not an easy parameter, the incorrect setting of it can lead to an explosion of messages and an exponential convergence time. This problem has been studied by Fabrikant et al. [5] and the origin of the problem has been attributed to the *path exploration* problem. This is a well known problem in the BGP comunity and it is experienced by a node when it enters in a transitory phase where it accept and publish not optimal paths towards the destination before reaching a stable state. *Path exploration* can lead to an enormous ammount of messages even with a small set of nodes [9].

As we saw in Section 4.2.1 that MRAI can influence the CFSMs of the nodes and their output signals, which impact could it have if it is not setted correctly?

I have then created an environment that resemble the study conducted by [5] using a topology like the one described in Section 3.1.2 with 3 rings. with different MRAI settings. The environment properties are presented in Table 4.4.

Property	Value
Seeds	$[1, 30]$
Signaling	"A", "AW", "AWA", "AWAW"
Withdraws delay	Uniform distribution between 5 s and 10 s, Uniform distribution between 10 s and 15 s
Announcement delay	Uniform distribution between 5 s and 10 s, Uniform distribution between 10 s and 15 s
Link delay	Uniform distribution between 0.5 s adn 3 s, uniform distribution between 2 s and 4 s

Table 4.4: Fabrikant experiments environment

In total for each signaling experiment this environment produces 240 runs. I have then introduced 4 different MRAI strategies for each different signal. The different MRAI strategies are the following one:

- ***Fixed* 30 s**: MRAI is fixed for each link to 30 s;
- ***No MRAI***: MRAI is fixed for each link to 0.0 s;
- ***Ascendent***: MRAI will be doubled at each leach $(1 - 2 - 4 - 8 - ...)$;
- ***Descendent***: Reverse of the ascendent case, MRAI will be divided by two at each leach.

Another important factor to consider during those experiments is the Implicit Withdraw (IW) capability of BGP. This parameter will influence the number of messages that will be transmitted.

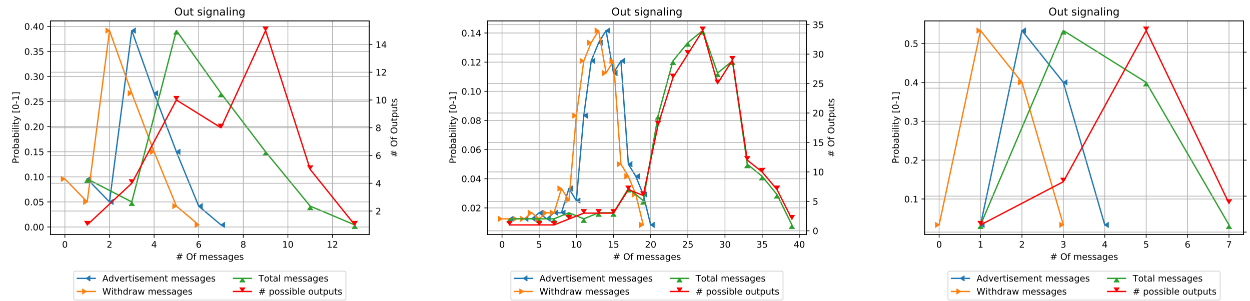
The results of all those different experiments, in terms of CFSM are exposed in Table 4.5

Signaling	IW	No MRAI		Fixed 30s		Ascendent		Descendent	
		$\|S\|$	$\|T\|$	$\|S\|$	$\|T\|$	$\|S\|$	$\|T\|$	$\|S\|$	$\|T\|$
"A"	Yes	12	19	15	26	7	12	16	24
	No	30	100	30	125	9	21	30	132
"AW"	Yes	52	181	37	103	24	71	40	80
	No	51	221	57	263	22	90	58	274
"AWA"	Yes	51	170	25	50	33	148	50	137
	No	69	364	37	180	30	203	66	419
"AWAW"	Yes	77	461	38	132	54	300	53	148
	No	78	500	62	429	48	350	66	441

Table 4.5: Fabrikant CFSMs results, $|S|$ is the dimension of the states set $|T|$ is the dimension of the transitions set, The worst results for each category are colored in gray, the topology contains 3 rings, as Figure 3.3

As is possible to see from the gray squares in Table 4.5 the more complex CFSMs are the ones without MRAI and with a descendent MRAI timing. The second case is the same described in [5] and the extreamly high number of transitions is caused by the *Path Exploration* problem. Is also noticeable that the IW has a huge effect on both the number of states and the number of transitions. This because there are less possible combination of input signals for the nodes. The opposit case in respect of the Descendent strategy obtain great results, even better than the actual standard of 30 s for each link. This performance improvement is caused by the fact that each leach will wait enough time to have more information from its predecessor in order to have more information to take the best decision.

The *Path Exploration* problem is also noticeable evaluationg the output signals of the last node of the chain. Results about the output signal of the node 8 (the last node of the gadget) are presented in Figure 4.6.



(a) Node 8 output signals study with ***Fixed* 30 s** strategy

(b) Node 9 output signals study with ***Descendet*** strategy

(c) Node 9 output signals study with ***Ascendent*** strategy

Figure 4.6: Output signal study of nodes 8 of the graph Figure 3.3 with an input signal of "AWA" at node with the ***Fixed* 30 s**, ***Descendet*** and ***Ascendent*** strategies, without the help of the IW

The first signal study, Figure 4.6a is the one that represent the actual standard of the protocol [10]. We can notice in that particular output study that the max lenght relevated of a signal is 13 and it's the last probable output, while the most probable output length is 5. While we can notice the *Path Exploration* problem by the spike of unique output signals with a length of 9, this mean that the node experienced some changes in its decisions. The worst case scenario is the one represented by Fig. 4.6b where the maximum length of output signal reaches almost 40 messages, but the most probable output signal have a length between 20 and 30. This is the marker of a lot of decision changes in the best path for the node 8. Opposit to that case we found the *Ascendent* strategy in Figure 4.6c where the number of output signals never used more than 7 messages. The node 8 in this last case almost never experienced the *Path Exploration* problem, thanks to the fact that most of the times the information it receives from the neighbourhod are already corrected.

In conclusion of this chapter we can say without doubts that MRAI influences the number of states experienced by a node and, confirming what has been sayid in [5], that an incorrect setting of it can lead to an explosion on the number of states and transitions. It is also noticeable that a different setting of MRAI can also lead to a better scenario than the standard one. Alternatives to the standard MRAI has been already presented Include citations and maybe find a better end of the chapter

5 BGP MRAI dependance

- Why BGP depends on MRAI?
- Why MRAI prevents messages explosions
- Previous works

5.1 Clique graph

- clique experiments
- messages vs convergence time

5.2 Internet like graph

- Environment state
- what is an internet like graph
- cite elmokashfi
- messages vs time

5.3 Pareto Efficiency Front

- There is space for improvements?

5.4 Strategy dependence

- Describe the convergence time dependance on MRAI
- Describe previous works on this track
- show the differences between different strategies

5.5 Signal dependance

- There is a dependance on the signal and on the effects of MRAI?
- Show the difference between different signals

5.6 Position dependance

- And how much is influent the position?
- Hierarchically?

6 RFD and MRAI correlation

- Expose more deeply what is RFD
- Expose previous studies about RFD
- Today RFD? Outdated

6.1 RFD on toy topologies

- What is the impact of RFD?
- In which occasion is present RFD?
- Clique
- Variations thanks to MRAI

6.2 RFC 2439 VS RFC 7196

- Time comparison between both of them
- how them react differently?
- why?

6.3 Mice VS Elephants

- What is Mice VS Elephants?
- How has been studied in the past?
- Introduce how MRAI affects mice VS elephants

7 Conclusion

- Wrap up
- Path exploration explosion of the FSM
- MRAI convergence dependency
- RFD and MRAI co-dependency

7.1 Future Works

:)

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Appendix A First Appendix

Abbreviations

ADV advertisement

AS Autonomous System

BGP Border Gateway Protocol

CFSM Communicating Finite-State Machine

DES Discrete Event Simulator

FSM Finite State Machine

IW Implicit Withdraw

MRAI Minimum Route Advertisement Interval

RIB Routing Information Base

RNG Random Number Generator

SPP Stable Paths Problem