802.11 Disassociation DoS attack Simulation Using Verilog*

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Abstract: - A number of Denial of Service (DoS) attacks in IEEE 802.11 are due to unauthenticated/ unencrypted management and control frames. Current IEEE 802.11 simulators deal with Physical and MAC layers and do not include the exchange of management and control frames, thus making it difficult to simulate an attack (DoS) and its possible solution. A basic IEEE 802.11 network simulator using Verilog is presented. Basic aim is to design a simulator using a hardware description language (HDL) such as Verilog, since the functions and protocols described in state machines are best simulated using a HDL. Besides simulation of a simple wireless network, the paper also presents simulation of a spoofed MAC disassociation DoS attack and one of its possible solutions. The proposed simulator includes the communication setup process and can be used for simulating other DoS attacks and their possible solutions.

Key-Words: - Network Simulator, IEEE 802.11, Verilog, Wireless LAN, Link layer simulation.

1 Introduction

Due to ease of installation, expansion, modification and maintenance, wireless technology is the first choice of today's network administrators and home users. IEEE 802.11, which was ratified in 1999, is the basic and widely adopted standard for WLANs [1]. The standard has been evaluated and updated in different periods but still provides space for improvements. One example is IEEE 802.11i, which was defined to address the security vulnerabilities of WLANs [2]. However, IEEE 802.11i is still vulnerable to many Denial of Service (DoS) attacks because of its unauthenticated management and control frames [3, 4]. This has made the WLANs an open area for research by communication experts. In relation, advancements and modifications in simulation/ verification procedures are also necessary being an important step in any research work

In IEEE 802.11 WLANs, the actions of an access point (AP) or a wireless client depends on their respective current states. These states are maintained at each end by a state machine and the transitions between these states are controlled by management / control frames. The Robust Security Network Association (RSNA) Establishment [2] is the communication setup procedure that involves transition between all states and establishment of keying material at both ends. Many DoS attacks involve spoofing of management frames used in RSNA establishment. In order to study the attacks and test the proposed solutions, simulation of RSNA establishment phase and exchange of relevant frames is required.

This paper presents a basic simulator using Verilog. The simulator includes the AP and wireless clients. RSNA establishment phase has been specially included to study different DoS attacks and test the proposed solutions. Enhancements have been introduced to simulate spoofed MAC disassociation DoS attack and one of its possible solutions [5]. The simulator is the first

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prototype and may require improvements / enhancements of functionality.

The paper is organized into sections. Section 2 introduces some of the existing simulators and section 3 gives brief introduction to Verilog. Section 4 describes basic simulator design and section 5 explains enhancements for simulation of spoofed MAC disassociation DoS attack and its solution. Section 6 gives sample simulation scenarios and finally conclusion is presented in section 7.

2 Network Simulators

Some of the network simulators that can be used for simulation of wireless networks are described here. These can be broadly divided into two categories i.e., Open Source Simulators and Commercial Simulators.

2.1 Open Source Simulators

Most widely used open source simulators include NS 2, OMNET++ and GloMoSim.

2.1.1 NS 2

Network Simulator2 (NS2) is a discrete event simulator that runs more efficiently on Linux platforms [6]. It is freely available and has an active user list to discuss the queries. Its complete source code including a decent documentation is available for potential users. Some tutorials on NS2 are also available on the web that can serve as a good starter. NS2 uses both C++ and OTCL. C++ is used for source coding the modules and OTCL for simulation control. These two are tightly bound with each other. NS2 has good support for wireless networks and 802.11 protocol is also well supported. However, NS2 does not provide support for the infrastructure mode in wireless networks. Detailed functioning of MAC is not included and Management frames are also simply discarded. Due to its object oriented programming any modification requires understanding of complete code of the simulator and specially the C++ and OTCL binding.

2.1.2 OMNET++

OMNET++ is a component-based, modular and open-architecture simulation environment having strong Graphic User Interface (GUI) [7]. Its use is free for academic and non-profit purposes. It also has a user list which is a support forum. Its INET framework deals with simulations of wired, wireless and ad-hoc networks. However, its wireless modules are not yet fully developed and only support ad hoc mode which has no functionality regarding authentication / association etc. New modules can be added but sketchy documentation makes it very difficult.

2.1.3 GloMoSim

GloMoSim (Global Mobile Information Systems Simulation Library) is mainly a simulator for wireless networks [8]. It's Academic and research version is free to download (from an .edu domain). Its design is based on a layered approach, which is similar to seven layers of OSI model. It makes use of Parsec (Parallel Simulation Environment for Complex Systems) [9] for parallel discrete event simulation. In order to understand and modify the source, the user needs extensive knowledge of Parsec. QualNet is commercial product that is based on GloMoSim [10].

2.2 Commercial Simulators

Most commonly used commercial simulators include OPNET, NetSim etc.

2.2.1 OPNET

The network simulator OPNET (Optimized Network Engineering Tool) is easy to use and is having excellent graphical user interface [11]. It has different versions such as academic, research, complete etc. Only academic version is freely available with limited features, less documentation and no support. The current academic version (IT Guru Academic Edition Build 1996) does not have detailed functions about wireless networks especially infrastructure mode. It is impossible to make modification / additions in academic version.

2.2.2 NetSim

NetSim is a discrete event simulator with an object based modeling approach [12]. It includes models for various LAN and WLAN protocols. It has two versions, a standard version and an academic version. It is a good teaching and learning tool. Modifications in its source code are however difficult being a commercial product.

3 Verilog

Verilog is a Hardware Description Language (HDL). Hardware Description Language is used to describe a digital system; it can be as simple as an adder or as complex as a microprocessor. Further, HDL can define the system at different levels of abstraction. The basic difference between a programming language and a HDL is that HDL has modules that run concurrently like a hardware, further, timings can also be coded in the description.

To standardize Verilog an IEEE Standards Group for Verilog (VSG) was established in 1993. The first standard, IEEE 1364-1995, was released in 1995 [13]. The latest standard is Version C of IEEE 1364-2001 [14]. The standardization has further increased the use of Verilog.

The basic purpose of Verilog or any HDL is to simulate a digital system. This simulation is carried out to test the design before going for final hardware prototyping. AP and wireless network cards are essentially a digital system and can be best simulated in HDL specially those with hardware acceleration functions. Further in a WLAN, each AP or wireless client has to operate independently and concurrently as a separate hardware device. This can be best simulated in Verilog.

Designing in Verilog involves four steps (Fig 1). Step 1 defines the system using Verilog. In this step already defined modules can also be used. These can be vendor defined modules, for example Microprocessor 8051. Step 2 is compiling the design file. This is followed by step 3 which is simulation. Simulation results may be available in textual or graphical form. Debugging step involves checking/ analyzing the simulation results and modifying the design files.

Step 1 can be performed using any text editor, for step 2, 3 and 4 many tools are available. A list of free tools for Verilog can be found at Verilog. Net [15].

For our simulation we used ModelSim Xilinx Edition III v6.1e which is a free version with decent functionality. ModelSim is a verification and simulation tool for hardware. The hardware to be verified or simulated is described using hardware description languages such as VHDL, Verilog etc. ModelSim has many supporting functions such as waveforms that can be observed to confirm the functioning of a device.

4 Simulator Design

The simulator consists of a number of modules that have been integrated through a project in ModelSim called WLAN. The main modules are media, carrier sense, receive, transmit, test-bench and log modules. The relationship between different modules is shown in Fig 2. Test bench controls the simulation and log gives the results of simulation. Media module makes communication possible between AP and wireless nodes. The details of the simulator are explained in next sub sections.

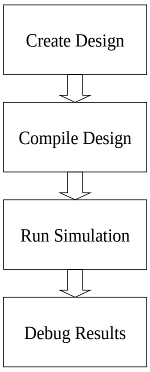


Fig 1: Steps in System Design with Verilog

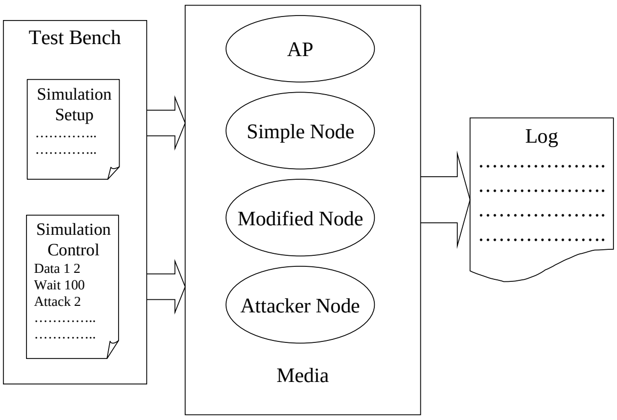


Fig 2: Simulator Design

4.1 Frame Format

The frame format used is given in Fig 3. It is essentially the IEEE 802.11 standard frame with some simplification.

2 Bits	4 Bits	1 Bit	1 Bit	48 Bits	48 Bits	48 Bits	4 Bits	12 Bits	48 Bits	0 – 2312 Bytes
Type	Sub Type	To DS	From DS	Addr 1	Addr 2	Addr 3	Frag no	Seq No	Addr 4	Frame Body

Fig 3: Frame Format

4.2 Media Module

The media module simulates wireless media. It’s a shared space that is used for writing the sent data. When a node needs to send a frame, it writes it to the media space. All nodes then check the media for their addresses and read the frame accept if it’s for them else discard it. Two status flags are used, first to indicate whether media is busy or idle and second to indicate whether node is sending or receiving a frame.

4.3 Carrier Sense Module

This module is implemented in all nodes and AP. It is basically a simplified version of carrier sense multiple access / collision avoidance. Any node that has a frame to send monitors the media, when media is free it generates a random backoff and waits for that backoff before sending the frame. If during the wait state the media gets busy, the node stops the backoff down counter and waits for the media to be free again. When media is free it again starts its backoff down counter from the stopped state and waits till counter is zero after that it sends the frame. The flow is shown if Fig 4.

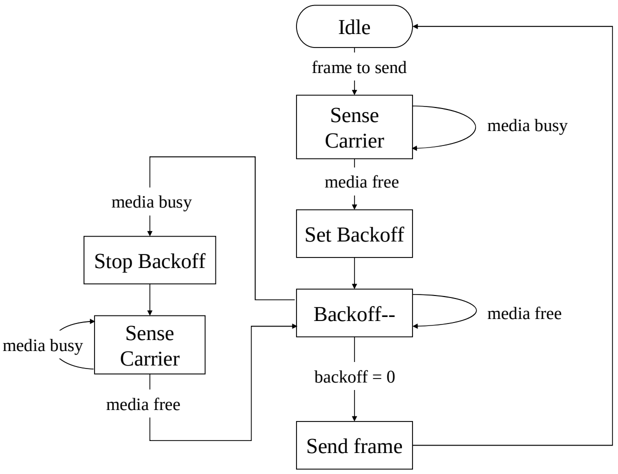


Fig 4: Flow Diagram – Carrier Sense Module

4.4 802.11 /802.1x State Machine

The state machine maintains authentication /association state of wireless node and AP. AP maintains a separate state machine for each of its authenticated / associated wireless nodes. Both the send and receive modules make use of state machine while processing the frames. AP and wireless client both start with state 1. Client requests authentication using Open System authentication to AP. On successful completion of authentication, both AP and wireless client transit to state 2. In state 2, wireless client initiates association request and on successful association both transit to state 3. In state 3, depending on authentication mechanism, 802.1x authentication messages will be exchanged. Pair wise Master Key (PMK) is established both at wireless node and AP after successful authentication. The 4-way handshake follows to generate keys for data encryption and data integrity. Both the AP and client are in state 4 and can use data encryption using generated keys. Note that on receiving a Disassociation message the state machine transits back to state 2 whether previously in state 3 or state 4. As authentication server has not been implemented in simulator therefore the transition to state 4 and establishment of keys is implicit to transition to state 3. State transitions are shown in Table 1.

Table 1: 802.11 / 802.1x State Transition Table

		Next State		
		State 1 Unauthenticated-Unassociated	State 2 Authenticated-Unassociated	State 3 Authenticated-Associated
Current State	State 1 Unauthenticated-Unassociated		Successful Authentication	
	State 2 Authenticated-Unassociated	Deauthentication Notification		Successful Association
	State 3 Authenticated-Associated	Deauthentication Notification	Disassociation Notification	

4.5 Send Module

Send module is implemented in AP and wireless nodes. When there is packet to send and carrier sense module has set send ready flag then the node is ready to send frame. Before sending the frame the current state of receiving node is checked and if current frame can be sent according to MAC protocol then send action is performed else the frame is discarded and associated actions are performed.

4.6 Receive Module

Receive module is implemented in AP and wireless nodes. After transmitting the frame the transmitting node changes the status of media to receiving. On this all nodes check the frame and if receiving address matches to that of the node then frame is received. After receiving the frame it is processed or dropped according to the current state of 802.11 state machines. Table 2 and 3 show the actions performed on receiving a frame by wireless node and AP respectively.

Table 2: Actions by Wireless Node on receiving a frame

		Current State		
		Unauthenticated Unassociated - UU	Authenticated Unassociated - AU	Authenticated Associated - AA
Received Frame	Association Response	1. Drop frame 2. Send Deauthentication	1. Change state to AA	1. Drop frame
	Disassociation	1. Drop frame 2. Send Deauthentication	1. Drop frame	1. Change state to AU
	Authentication Response	1. Change state to AU	1. Drop frame	1. Drop frame
	Deauthentication	1. Drop frame	1. Change state to UU	1. Change state to UU
	Data	1. Drop frame 2. Send Deauthentication	1. Drop frame 2. Send Disassociation	1. Process frame

Table 3: Actions by AP on receiving a frame

		Current State		
		Unauthenticated Unassociated - UU	Authenticated Unassociated - AU	Authenticated Associated - AA
Received Frame	Association Request	1. Drop frame 2. Send Deauthentication	1. Send Association Response	1. Send Association Response 2. Change state to AU
	Disassociation	1. Drop frame 2. Send Deauthentication	1. Drop frame	1. Change state to AU
	Authentication Request	1. Send Authentication Response	1. Send Authentication Response 2. Change state to UU	1. Send Authentication Response 2. Change state to UU
	Deauthentication	1. Drop frame	1. Change state to UU	1. Change state to UU
	Data	1. Drop frame 2. Send Deauthentication	1. Drop frame 2. Send Disassociation	1. Process frame according to Destination's state

4.7 Test Bench Module

Test bench module is the main / top-level module of simulator. Wireless network to be simulated is defined in this module. It instantiates and interconnects different devices in simulation such as AP, media, wireless nodes etc. The simulation to be performed is also defined in the test bench. It also serves as application layer providing data to nodes for transmission. Test bench can access and modify internal states of different module thus making comprehensive testing / simulation possible.

The sequences of events that take place are defined in test bench, such as, start of communication setup process, Data to be sent by a wireless client, timings of different events etc.

4.8 Log Module

Log module defines the logs that are generated by each wireless node and AP. Every device makes an entry to log file whenever it performs some action. On termination of simulation the log gives detailed account of the sequence of events performed by various devices. The log can be observed to check the behavior of any device. The legend and layout of log are given in Table 4 and Fig 5 respectively.

Table 4: Log - Legend

S/ No	Action Symbol	Meaning
1	r	Frame received
2	s	Frame sent
3	d	Frame dropped
4	p	Frame processed
5	Q	Frame enqueued
6	D	Frame dequeued
7	c	Collision detected
8	x	No frame to send

Time	Action	At node	Type	Sub type	To DS	From DS	RA	TA	DA	SA	Seq No	Remarks

Fig 5: Log - Layout

5 Simulator Enhancements

Enhancements are made in basic design (described in section 4) to simulate spoofed MAC disassociation DoS attack and its solution given in [5].

5.1 Attacker Node

A new type of wireless node, attacker node, is defined. It is used to launch DoS attacks by sending spoofed disassociation messages to victim nodes. Its send module is modified for this purpose. The instructions to launch attack are issued to attacker node via test bench module. The Attacker node need not to receive data so its receive module can be disabled. Further carrier sense module of attacker node can also be modified to incorporate selfish behavior. Both the Novice and Expert attacker nodes are defined [5]

5.2 Modified Node

Two types of modified nodes are defined. The first type, Modified Node (SN), incorporates only simple sequence number monitoring solution. The second type, Modified Node (PSN), incorporates randomized sequence number based solution. Both solutions are defined in [5]. The use of pseudo randomized sequence number instead of monotonically increasing sequence number is incorporated. In both cases the major modifications are made in state machines.

5.3 Access Point

AP is also modified in such a manner that it is compatible with both modified nodes and the simple node. Now AP can be used to establish a network having a mix of modified and simple nodes. This is necessary in order to check/compare the effectiveness of attack on different types of nodes.

6 Sample Simulations

Two simulation scenarios are used, one for simulation of a simple wireless network with different number of nodes and other with attacker / modified nodes.

6.1 Simulation Scenario 1

The simulation scenario comprises of wireless network in infrastructure mode having an access point (AP) and three wireless nodes. The network is shown in Fig 6.

6.1.1 Simulation Conducted

First of all the normal functioning of AP and wireless nodes was checked. For this a wireless network consisting of two wireless nodes and AP was simulated. Data was transferred between two wireless nodes via AP. This involved completion of communication setup process. The recovery from different intermediate states was also checked by controlling states via test bench. The results were checked by both, the waveform and the log. Waveform graphically shows the transition to states, sending / receiving of frames, updating of different variables/ states. The log is more concise and only provides the actions performed at various devices along with time and other important data. A partial log output is shown in Fig 7.

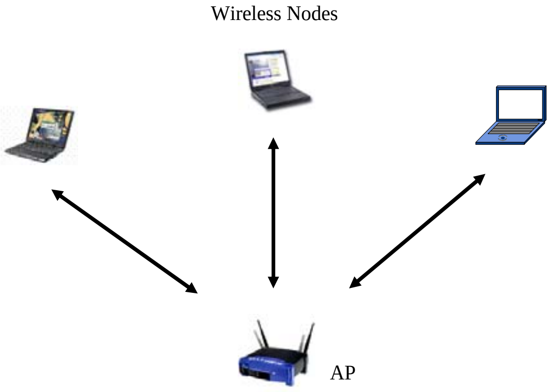


Fig 6: Simulation Scenario 1

```
 49,  Q,    1,  2, 0,                          2,    1,          Data to send
180,  D,    1,  2, 0,                          2,    1,          Frame to send
180,  Q,    1,  2, 0,                          2,    1,          Cannot send: UU
180,  Q,    1,  0,11,                        255,    1,          AuthReq
181,  D,    1,  0,11,                        255,    1,          Frame to send
183,  s,    1,  0,11,  0,0,  255,     1,  255,    1,  3714,   Data sent
185,  r,  255,  0,11,  0,0,  255,     1,  255,    1,  3714,
185,  p,  255,  0,11,  0,0,  255,     1,  255,    1,  3714,   AuthReq
185,  Q,  255,  0, 8,                          1,  255,          AuthResp
240,  D,  255,  0, 8,                          1,  255,          Frame to send
242,  s,  255,  0, 8,  0,0,    1,  255,    1,  255,  1636,   Data sent
245,  p,  255,  0, 8,                          1,  255,          New state AU
245,  r,    1,  0, 8,  0,0,    1,  255,    1,  255,  1636,
245,  p,    1,  0, 8,  0,0,    1,  255,    1,  255,  1636,   New state AU
330,  D,    1,  2, 0,                          2,    1,          Frame to send
330,  Q,    1,  2, 0,                          2,    1,          Cannot send: AU
330,  Q,    1,  0, 0,                        255,    1,          AssocReq
331,  D,    1,  0, 0,                        255,    1,          Frame to send
333,  s,    1,  0, 0,  0,0,  255,     1,  255,    1,  3715,   Data sent
335,  r,  255,  0, 0,  0,0,  255,     1,  255,    1,  3715,
335,  p,  255,  0, 0,  0,0,  255,     1,  255,    1,  3715,   AssocReq
335,  Q,  255,  0, 1,                          1,  255,          AssocResp
350,  D,  255,  0, 1,                          1,  255,          Frame to send
352,  s,  255,  0, 1,  0,0,    1,  255,    1,  255,  1637,   Data sent
```

Fig 7: Partial Log – Simulation Scenario 1

Second set of simulations were conducted with AP and three wireless nodes. Data transfers between three wireless nodes were simulated. The internal states of wireless clients were then altered to check their response and recovery. Internal states of AP were also modified to confirm its response. The log was observed which confirmed that the network was performing as per design parameters.

Further simulations were also conducted by changing the sequence of events in Test bench module. The network was then expanded to five wireless clients. The functionality of Carrier sense module was specially checked to confirm that each wireless client has equal probability of getting the access.

6.2 Simulation Scenario 2

The simulation scenario comprises of wireless network in infrastructure mode having an access point (AP) and five wireless nodes. Two of the wireless nodes have modified protocols one incorporating the simple sequence number based solution (Modified Node - SN) and the other incorporating pseudo randomized sequence number based solution (Modified Node - PSN). Out of the remaining three, one is simple node (Simple Node) without modified protocol and last two are attacker nodes (Expert Attacker and Novice Attacker). Attacker nodes launch disassociation DoS attacks. The network is shown in Figure 8.

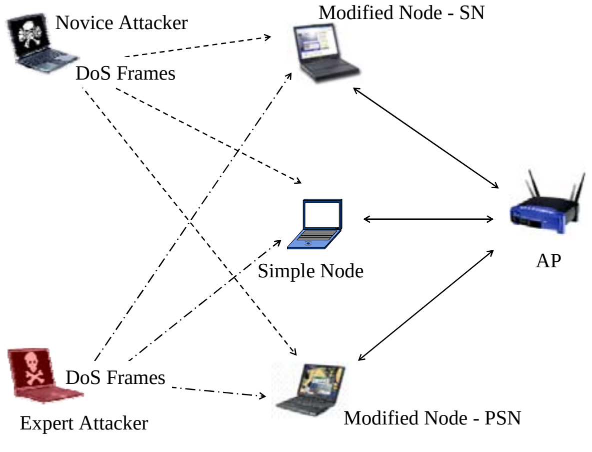


Fig 8: Simulation Scenario 2

6.2.1 Simulation Conducted

First set of simulations were conducted to check the effectiveness of DoS attacks launched by attacker node. For this the attacker nodes were added to simple network. The attacks were launched on individual nodes. The nodes were forced in different possible states of communication setup process and then DoS attacks were repeatedly conducted.

Second set of simulations were conducted to verify the proposed solution. For this a wireless network consisting of a simple wireless node, both modified wireless nodes, both attacker nodes and AP was simulated. Different communication links were setup involving a mix of simple and both the modified nodes. The communications between nodes were setup through the AP. The different data transfers sessions between modified and simple nodes were initiated while forcing the nodes in different initial states. This confirmed the correct functioning of AP in relaying data between these different types of nodes. DoS attacks were launched for simple and both modified nodes. The processing of legitimate disassociation notification was also checked by changing states of devices.

The results showed that the simple node always failed to detect the attack, whether form Novice or Expert Attacker. The Modified Node - SN was successful most of the time in detecting and preventing the attack from Novice Attacker whereas it failed to detect the attack of Expert Attacker. The Modified Node - PSN successfully detected and prevented the disassociation DoS attack from both of the attackers. The simulation results also confirmed the percent success probability of both the attackers against both the solutions. (Figure 9)

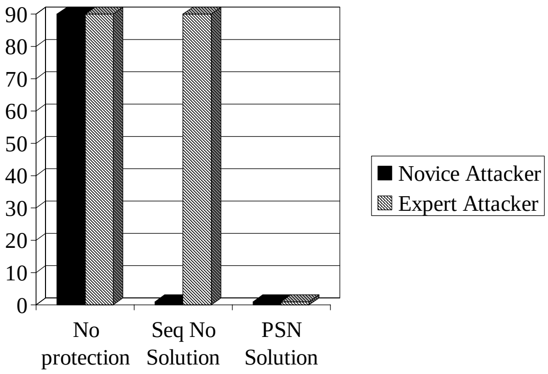
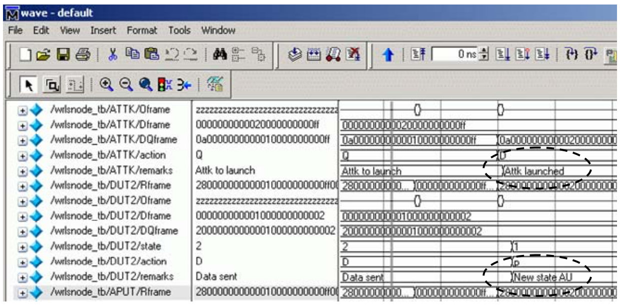


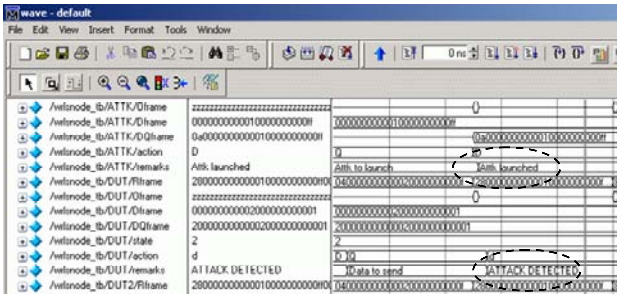
Fig 9: Percent Success probability (From [5])

Figure 10 shows one of the event traces when simple node fails to detect the attack. Figure 11 shows one of the event traces when the Modified Node - PSN successfully detects and prevents the attack from Expert Attacker. The legitimate disassociation frames were always processed as per the protocol (Figure 12).



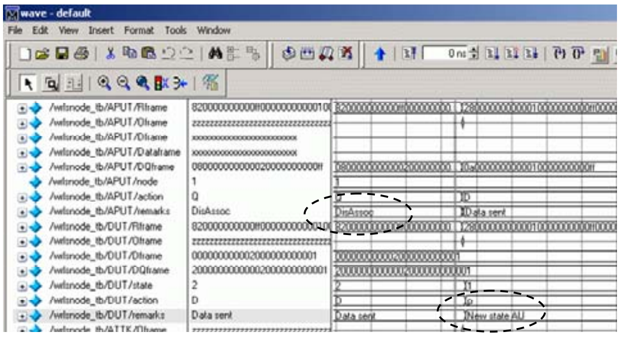
```
/wrlsnode_tb/ATTK/Oframe      zzzzzzzzzzzzzzzzzzzzzzzzzzzzzzz
/wrlsnode_tb/ATTK/Dframe      000000000002000000000ff
/wrlsnode_tb/ATTK/DQframe     0a000000000001000000000ff
/wrlsnode_tb/ATTK/action      Q
/wrlsnode_tb/ATTK/remarks     Attk to launch
/wrlsnode_tb/DUT2/Rframe      280000000000010000000000ff0(
/wrlsnode_tb/DUT2/Oframe      zzzzzzzzzzzzzzzzzzzzzzzzzzzzzzz
/wrlsnode_tb/DUT2/Dframe      000000000001000000000002
/wrlsnode_tb/DUT2/DQframe     20000000000001000000000002
/wrlsnode_tb/DUT2/state       2
/wrlsnode_tb/DUT2/action      D
/wrlsnode_tb/DUT2/remarks     Data sent
/wrlsnode_tb/APUT/Rframe      280000000000010000000000ff0(
```

Fig 10: Failure of Attack Detection by Simple Node



```
/wrlsnode_tb/ATTK/Oframe      zzzzzzzzzzzzzzzzzzzzzzzzzzzzzzz
/wrlsnode_tb/ATTK/Dframe      000000000001000000000ff
/wrlsnode_tb/ATTK/DQframe     0a000000000001000000000ff
/wrlsnode_tb/ATTK/action      D
/wrlsnode_tb/ATTK/remarks     Attk launched
/wrlsnode_tb/DUT/Rframe       280000000000010000000000ff0(
/wrlsnode_tb/DUT/Oframe       zzzzzzzzzzzzzzzzzzzzzzzzzzzzzzz
/wrlsnode_tb/DUT/Dframe       000000000002000000000001
/wrlsnode_tb/DUT/DQframe      20000000000002000000000001
/wrlsnode_tb/DUT/state        2
/wrlsnode_tb/DUT/action       d
/wrlsnode_tb/DUT/remarks      ATTACK DETECTED
/wrlsnode_tb/DUT2/Rframe      280000000000010000000000ff0(
```

Fig 11: Attack Detection by Modified Node



```
/wrlsnode_tb/APUT/Rframe      82000000000ff00000000000010(
/wrlsnode_tb/APUT/Oframe      zzzzzzzzzzzzzzzzzzzzzzzzzzzzzzz
/wrlsnode_tb/APUT/Dframe      xxxxxxxxxxxxxxxxxxxxxxx
/wrlsnode_tb/APUT/Dataframe   xxxxxxxxxxxxxxxxxxxxxxx
/wrlsnode_tb/APUT/DQframe     0800000000000200000000ff
/wrlsnode_tb/APUT/node        1
/wrlsnode_tb/APUT/action      Q
/wrlsnode_tb/APUT/remarks     DisAssoc
/wrlsnode_tb/DUT/Rframe       82000000000ff00000000000010(
/wrlsnode_tb/DUT/Oframe       zzzzzzzzzzzzzzzzzzzzzzzzzzzzzzz
/wrlsnode_tb/DUT/Dframe       000000000002000000000001
/wrlsnode_tb/DUT/DQframe      20000000000002000000000001
/wrlsnode_tb/DUT/state        2
/wrlsnode_tb/DUT/action       D
/wrlsnode_tb/DUT/remarks      Data sent
/wrlsnode_tb/ATTK/Oframe      zzzzzzzzzzzzzzzzzzzzzzzzzzzzzzz
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Fig 12: Processing of Legitimate Disassociation Notification by Modified Node

7 Conclusion

The WLAN standards are still in development phase, there are still many open and interesting research areas in this field. One of the important steps in research is to check the results through simulation. In this paper we have designed a basic WLAN simulator using a HDL. WLAN standard is based on state machines and state machines can be best simulated using a HDL. Further if a modifications / solutions are tested through HDL then there are all the more chances that it can be implemented in hardware. The simulator can be expanded by adding reusable libraries such as vendor specific library/ module for an AP or a wireless client. This makes simulation more realistic.

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