Integrated LTspice and NS-3 Power Management Simulation for Energy Harvesting

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***Abstract*—LTspice is a popular and free circuit simulating package while NS-3 is an open source network simulator. Integrating these two popular simulation packages is an ideal scenario where an output from LTspice such as power can be an input to network modules in NS-3. The aim of this paper is, therefore, to integrate LTspice and NS-3 simulators in order to forge a strong research collaboration between two domains (electronics and networking). The integration of these simulators have be evaluated and validated by using power management use case in energy harvesting. Preliminary results based on Fuzzy control logics for the power management system have shown that the integration to be effective. The downtime ratio and energy efficiency utilization were preferable compared to the scenario where fuzzy control system was not implemented.**

***Index Terms*—Piezoelectric, WSN, Energy, Power Management, NS-3, LTspice, Fuzzy System.**

I. Introduction

The growing integration of Wireless Sensor Networks (WSN) in industries and critical infrastructures requires capabilities beyond the limits of the existing development tools. The performance of WSN needs to be evaluated before deployment, either by on-site experiments or simulation. The on-site performance evaluation is time and cost consuming, cannot easily cover the full range of expected operational conditions, and is not repeatable with real sensor nodes. Simulations, therefore, are the only efficient means to evaluate the performance of wireless networks. A major problem associated with most current network simulators in a situation whereby energy is required to power network elements is that the implementation of energy models are different from the ones in real devices. Therefore, in many cases, it is difficult to conclude whether certain performance characteristics are due to specific protocol functionality or is just a feature of a particular implementation in a network simulator.

NS-3 or the network simulator 3 is an open source discrete event network simulator [1]. It is popular in academia because it easily be extended due to its open source model and it has extensive support and online documentation. NS-3 is extensively used in the routing and multicast protocols simulations, among others, and is widely used in ad-hoc networking research. NS-3 can support a long list of mostly used network protocols, providing simulation results for both wired and wireless networks.

LTSpice is a free-ware software for designing and analysis circuit. It is a waveform viewer and schematic capture with models and enhancements for improving switching regulators simulations [2]. It can support unlimited number of nodes and it can provide a rich of libraries that among other circuits, it includes the LTC3588-1 power management integrated circuit.

The integration of these simulators packages will therefore compliment each other. NS-3 will benefit from different simulated real integrated circuit nodes and LTspice will benefit from network communication protocols which are widely available in NS-3. The integration of NS-3 and LTspice will based on the scenario of power management for energy harvesting.

Power management for energy harvesting is very important, in the case of WSN in aircraft, Structural Health Monitoring (SHM) is made up of permanently monitoring key parameters for aging effects prediction. The major goal is to reduce cost and improve mechanical safety by deploying scheduled maintenance by predictive maintenance [3]. For efficient SHM, WSN nodes are required to have enough energy for transmitting key monitored parameters. In order to ensure that enough energy is available at critical moments of transmission, energy harvesting from ambient sources such as vibration and thermal is used to power WSN nodes.

A WSN node can harvest energy from several ambient sources, vibration energy harvesting using Piezoelectric Generation (PEG) and Thermoelectric Generation (TEG) can be a reliable way to harvest energy in the aircraft environment. PEG can harvest higher energies as the airplane wings vibrate because of air turbulence, engine vibrations, weight and stiffness of the wings. TEG can also be exploited, around the engine.

In order to demonstrate that the integration between LTspice and NS-3 is feasible, this paper proposes to integrate LTspice and NS-3 by implementing power management system for energy harvesting whereby energy harvested via Peizoelectic source in LTspice is fed into NS-3 via a communication channel.

The main contribution of this paper is to propose the integrating between LTspice and NS-3 for power management for energy harvesting scenario.

The rest of this paper is organized as follows, Section II presents the design of the integration between LTspice and NS-3. The implementation of the design integration will be presented in Section III. Results and evaluation are presented in Section IV and conclusion and future work are discussed in Section V.

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II. LTSPICE AND NS-3 INTEGRATION DESIGN

A. LTSpice

LTC3588-1 is a Nanopower Energy Harvesting Power Supply [4] which in this integration is used in LTspice to supply power to the NS-3 network simulator.

The LTC3588-1 is able to integrate the high efficiency buck converter with low-loss full-wave bridge rectifier in order to form a full energy harvesting solution which is optimized for high output impedance energy sources (e.g., piezoelectric, solar, and magnetic transducers). ”An ultra-low quiescent current under-voltage lockout (UVLO) mode with a wide hysteresis window allows charge to accumulate on an input capacitor until the buck converter can efficiently transfer a portion of the stored charge to the output. In regulation, the LTC3588-1 enters a sleep state in which both input and output quiescent currents are minimal” [4]. To maintain regulation, the buck converter is set to on and off as required.

1.8V, 2.5V, 3.3V and 3.6V are four output voltages which are pin selectable and can go up to 100 mA as an output of continuous current [4]. However, a higher output current burst can be accommodated by sizing the output capacitor. The input protective shunt which is set at 20V can enable greater energy storage for an amount of input capacitance in place. LTC3588-1 power supply with piezoelectric harvesting node is depicted in Fig. 1. The modules used in this integration are V1 which is the Voltage Source functioning as the Sine wave for Piezoelectric energy harvester and V2 which is the Voltage Source functioning as the Pulse for Control signal of the ADC enable command.

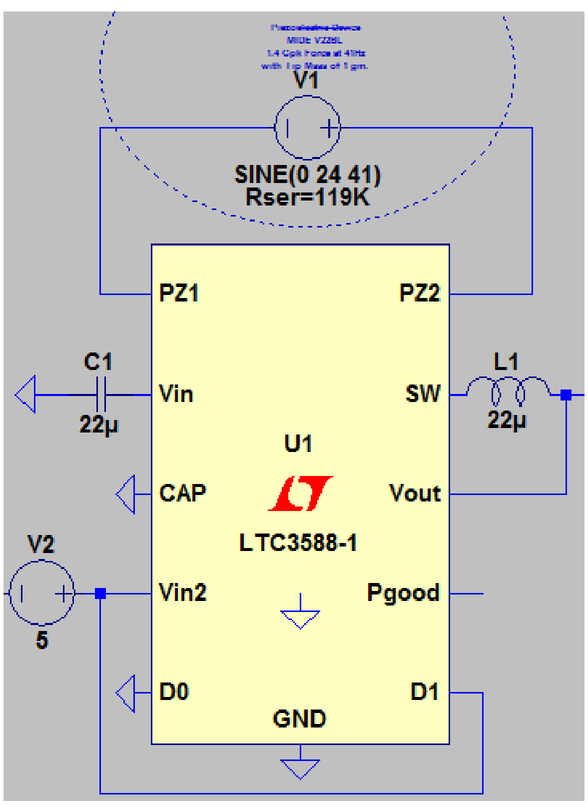

Fig. 1: LTC3588-1 - power supply

The output of V1 and V2 are encapsulated into a reliable TCP connection and transmitted to NS-3 simulation (Fig. 2).

B. NS-3

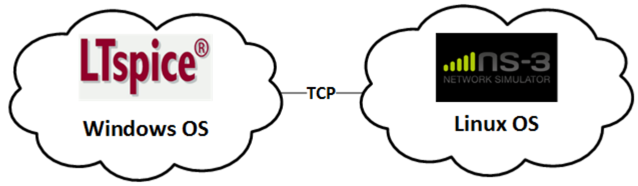

Fig. 2: LTspice and NS-3 TCP connection

In NS-3, LinuX Containers (LXCs) are implemented for the integration between NS-3 and LTspice through the TCP transmission protocol. Once the TCP segments are received, the values of V1 and V1 are passed to the relevant modules for WSN nodes communication. Some studies already proposed to integrate Linux containers. Connecting NS-3 with LXCs for simulating several applications running in mobile environments has been presented in the work of Zhang and Qin called TapRouter [5], and in the work of Skjegstad et al. [6]. Moreover, the connection of several Network Simulators (NS-3s) that are running inside Linux containers is presented in the work of Calarco and Casoni called NetBoxIT [7].

NS-3 provides realistic network models which simulate physical/link. This is the reason why it is widely used and researched in academic institutions. It is also natively supporting various emulated interfaces and tap devices. It supports real time simulations where data is treated by the emulators in the same timing it would have when transmitted over the real network [7].

Linux containers are a user space interfaces for the Linux kernel containment attributes. With LXCs, Multiple isolated Linux systems can be run in a single box [8]. LXCs depends on several kernel attributes for processes containment, these are kernel namespaces (e.g., interprocess communication, Unix Time Sharing System, mount, Process ID, network and user), Application Armour and Security-Enhanced Linux profiles, Secure Computing policies, chroots, kernel capabilities and control groups (cgroups). Amongst various virtualization techniques such VMware, VirtualBox, QEMU and LXC, authors in [7] found that LXCs can achieve the best performance in terms of best throughput and negligible computing overhead.

Fig. 3 depicts the connection between LXC connectivity via veth and tap devices. The connection between NS-3 with a set of Linux containers is via NS-3 native support of tap devices bridged with containers virtual Ethernet interface. NS-3 simulation parameters were as follows,

- Number of WSN nodes =2
- Time slot = 20ms
- Start Time = 0.0s
- Simulation time = 10 mins
- Distance between nodes = 20m
- Wireless protocol used is 802.15.4 with TX = 0.0174J and RX = 0.0197J

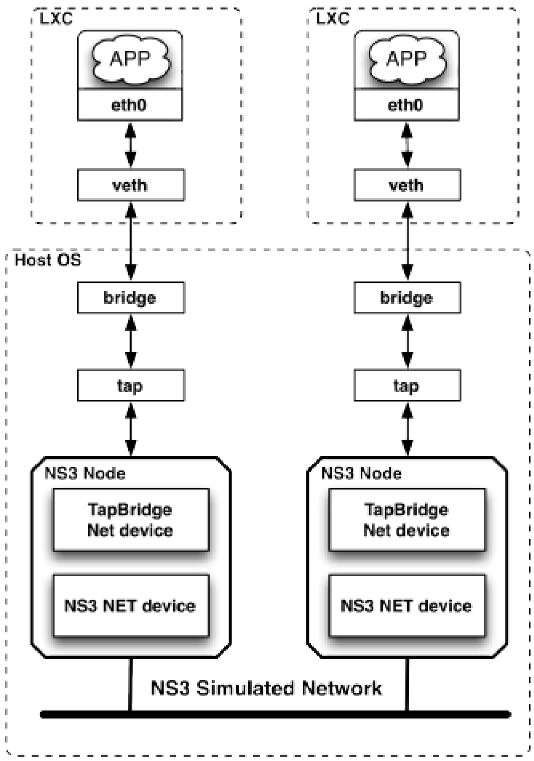

Fig. 3: LXC connectivity via veth and tap devices

C. Fuzzy Control System

The integration is based on fuzzy control system. Fuzzy logic endeavours to methodically and scientifically imitate human thinking and decision making [9]. It gives an instinctive approach to implement control systems, decision making and demonstrative frameworks in different branches of industry. Fuzzy logic has an excellent concept that closes the gap between human thinking and computational logic. Fuzzy logic enables scientists to exploit their empirical and heuristics knowledge characterised in the IF-THEN rules and transforms them to a functional block. Fuzzy logic systems was introduced by Professor Lofti Zadeh in 1965 [10] and are now applied in various advanced engineering applications, for instance fuzzy logic are used in intelligent control systems, fault detection, decision making, process diagnostics and expert systems.

A designed fuzzy system will process fuzzy and make decision. A designed fuzzy system consists of algorithms that can deploy inference. The fuzzy inference algorithms employ IF-THEN rules in intelligent control systems, fault detection, decision making, process diagnostics and expert systems. Fuzzy rules are created by the expert knowledge which is composed by AND/OR logical connectives. The total number of rules is obtained as a product of the number of sets of each input variables.

Linguistic variables are inputs to a fuzzy system and the outputs are linguistic variables together with linguistic terms definitions and fuzzy IF-THEN rules. A fuzzy inference is a method to evaluate the designed fuzzy system. This evaluation will compute output values from the input values to the fuzzy system. The fuzzy inference is made up of fuzzification, fuzzy rules and defuzzification.

The first step into fuzzy inference is fuzzification. It is a process in which the crisp sets are transformed into fuzzy sets. This process adds uncertainty to the system and the membership function is used to associate crisp sets into fuzzy sets.

Defuzzification is the opposite of fuzzification. In this process, fuzzy linguistic terms are converted into crisp sets. Fig. 4 depicts fuzzy control system and its components.

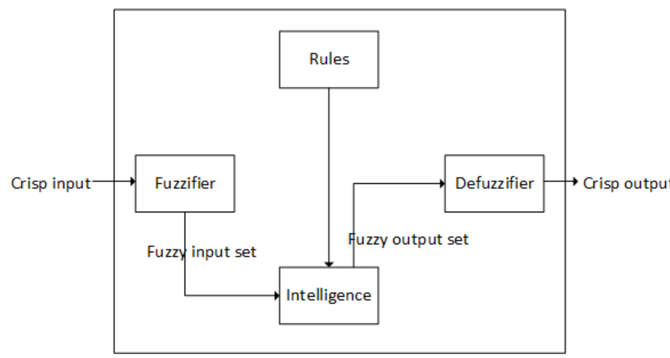

Fig. 4: Fuzzy control system

III. Implementation of the Design

The implementation of the design integration is based on Fuzzy control system and is implemented in NS-3 with the input data from LTSpice. Fuzzy based control system for power management was simulated in NS-3. The control system has three modules, the fuzzification, the inference, and the defuzzification.

- The fuzzification module transforms the physical inputs into fuzzy sets for the inference module. A fuzzy set is made up of an interval for the range of the input value and an associate normalized membership function defining the degree of the confidence of the input belonging to this range.
- The inference engine creates the control actions.
- The defuzzification unit maps the outputs to a physical value.

Fig. 5 depicts the proposed fuzzy control system design showing Harvested Energy (HE) and Residual Energy (RE) as inputs, inference engine and output actions.

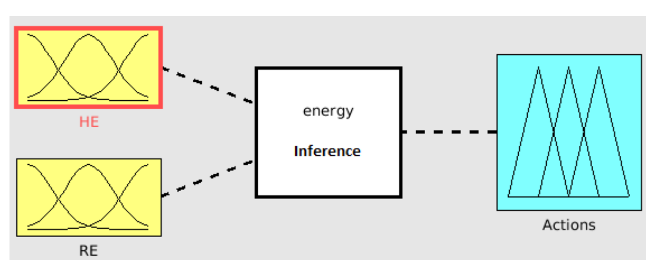

Fig. 5: Fuzzy control system design

A. *Fuzzification*

At time interval *t*, the following inputs are considered,

- **Harvested Energy (HE)**
  - Two fuzzy sets are proposed, LOW and HIGH
  - LHE is the lowest amount of harvested energy required to run the WSN
  - MHE is the threshold harvested energy considered to be HIGH
  - Normalized membership function,
    - LOW is 1 if HE $\leq$ LHE,
    - LOW is 0 if HE $\geq$ MHE and
    - LOW is x if LHE $<$ HE $<$ MHE
    - HIGH is 1 if HE $\geq$ MHE,
    - HIGH is 0 if HE $\leq$ LHE and
    - HIGH is x if LHE $<$ HE $<$ MHE

Fig. 6 depicts harvested energy membership function.

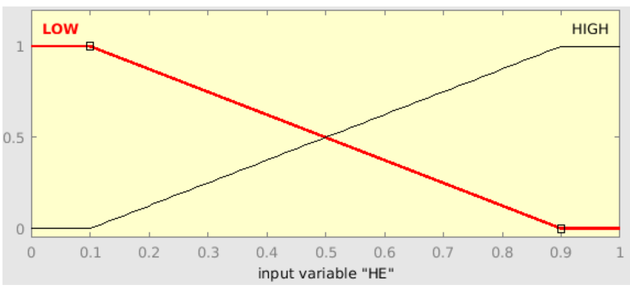

Fig. 6: Harvested energy membership function

- **Residual Energy (RE)**
  - Three fuzzy sets are, EMPTY and FULL
  - ERE is the amount of energy required to be reserved to run the WSN
  - FRE denotes that WSN has reserved sufficient RE
  - Normalized membership function,
    - FULL is 1 if RE $\geq$ FRE,
    - FULL is 0 if RE $\leq$ ERE and
    - FULL is x if ERE $<$ RE $<$ FRE
    - EMPTY is 1 if RE $\leq$ ERE,
    - EMPTY is 0 if RE $\geq$ FRE and
    - EMPTY is x if ERE $<$ RE $<$ FRE

Fig. 7 depicts Residual energy membership function.

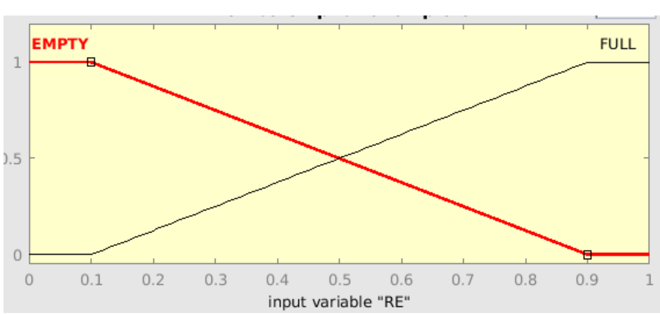

Fig. 7: Residual energy membership function

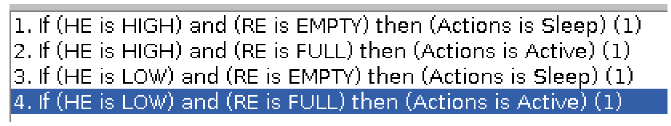
1. If (HE is HIGH) and (RE is EMPTY) then (Actions is Sleep) (1)
2. If (HE is HIGH) and (RE is FULL) then (Actions is Active) (1)
3. If (HE is LOW) and (RE is EMPTY) then (Actions is Sleep) (1)
4. If (HE is LOW) and (RE is FULL) then (Actions is Active) (1)

Fig. 8: Fuzzy IF-THEN rules

B. *Inference engine*

The inference engine is described by a set of 4 fuzzy IF-THEN rules in Fig. 8.

At time interval t, the following rules are considered,

- **R1:** If the amount of harvested energy is HIGH and the energy storage device is EMPTY, then part of the harvested energy is used to power the WSN and part of it will be stored.
- **R2:** If the amount of harvested energy is HIGH and the energy storage device is FULL, then the harvested energy is used to power the WSN.
- **R3:** If the amount of harvested energy is LOW and the energy storage device is EMPTY, then the harvested energy is stored and the WSN is put to sleep.
- **R4:** If the amount of harvested energy is LOW and the energy storage device is FULL, then the stored energy is used to power the WSN.

C. *Defuzzification*

This gets the output of the inference engine which is the energy as output of the rules.

The 3D view of the inference rules is illustrated in Fig. 9.

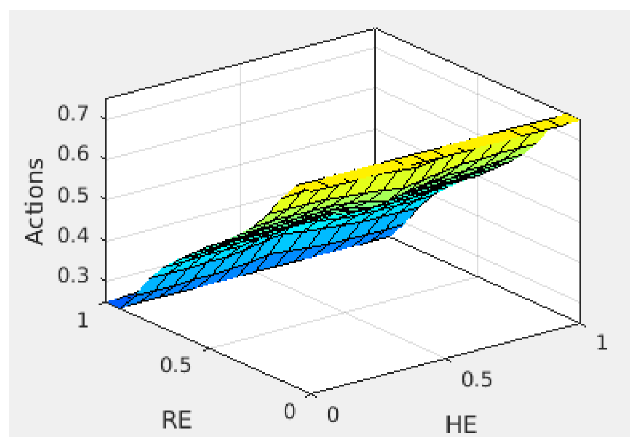

Fig. 9: Surface rules view

IV. Simulation Results

A. *Evaluation metrics*

Before presenting simulation results, evaluation metrics are outlined below, i.e., Downtime ratio and Energy Utilization Efficiency.

- Downtime ratio (DR)
  - The ratio spent on the sleep mode due to low energy to the total time of simulation. This value is between 0 and 1 included. If the value is 0 then there was no

sleep mode experienced due to low energy. If the value is one then the WSN was in the low energy state at all time during simulation

- Energy Utilization Efficiency (EUE)
  - The ratio of the total energy used by the WSN to the total energy harvested. This value is between 0 and 1 included. If the value is 0 then the WSN did not use the harvested energy at all during the simulation time. If the value is 1 then the WSN was using the harvested energy all the time during the simulation time.

B. Harvested Energy

Fig. 10 depicts the energy harvested from LTspice during simulation time. The simulation time was 10 minutes. During this simulation time, the maximum amount of energy harvested was 1.000928e-004J and the minimum energy harvested was 3.236360e-011J with an average of 4.74617e-05J.

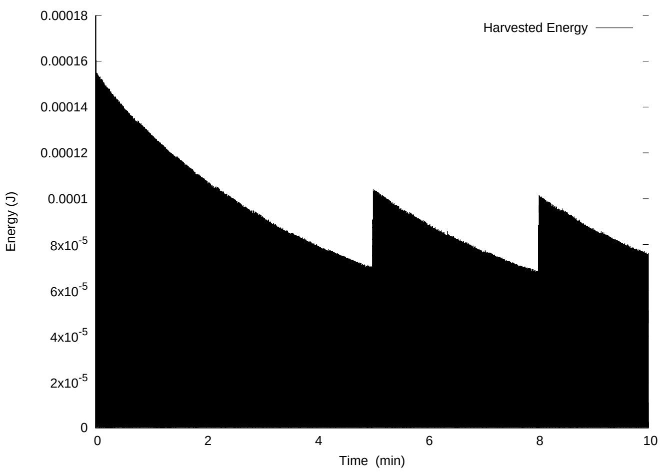

Fig. 10: Harvested energy

C. Residual Energy

Fig. 11 shows the residual during simulation time. The simulation time was 10 minutes. During this simulation time, the maximum amount of residual energy was around 1.0J and the minimum energy harvested was 6.003e-08J with an average of 0.63J.

D. Radio state

Fig. 12 shows the state of the WSN node, L denotes sleep mode and H indicates active state. From the simulation, there was a total of 1406 sleep states out of 15281 states. From these results the Downtime ratio (DR) is 0.3233. This illustrates that around 9% of the time the WSN was at sleep mode due to low energy as a result of Fuzzy system deployment. The goal is to keep the downtime ratio close to zero for efficient WSN communication.

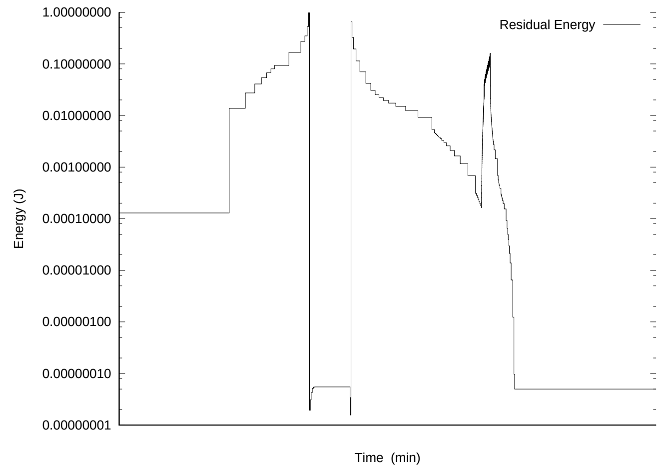

Fig. 11: Residual energy

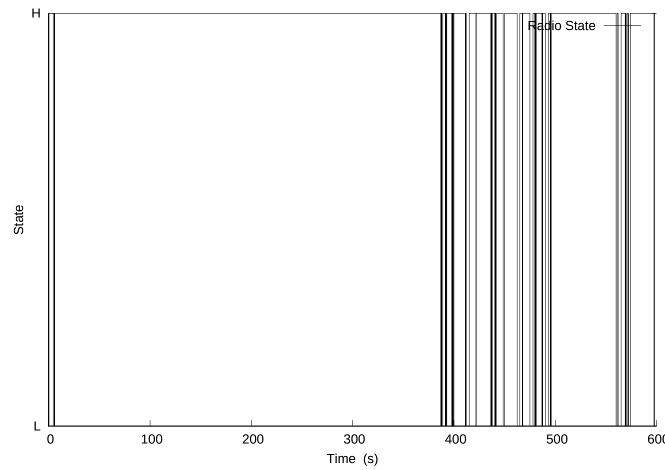

Fig. 12: WSN node radio state

E. Energy Utilization Efficiency

The amount of energy consumed by the WSN node is depicted in Fig. 13. From these results the Energy Utilization Efficiency (EUE) is 0.85. This means that 85% of the harvested energy was used to power the WSN operations. The other 15% might have been wasted due to any form or the WSN had enough energy for its own operations. The goal is to be as close as possible to 100% for efficient use of the harvested energy.

F. Fuzzy approach Vs non-fuzzy approach

The comparison is made between fuzzy and non-fuzzy (Fig. 14), it shows that fuzzy based approach performs better for two evaluation metrics (Downtime rate (DR) and Energy Usage Efficiency (EUE)). Fuzzy based power management system is capable to provide more energy efficient and less WSN sleeps due to low power storage.

V. Conclusion

This study was focused on the integration between LTSpice and NS-3, design, implementation and testing of a WSN based

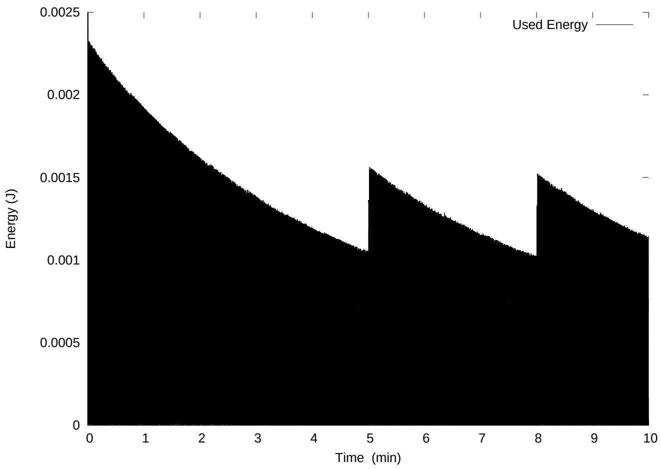

Fig. 13: Energy Utilization Efficiency

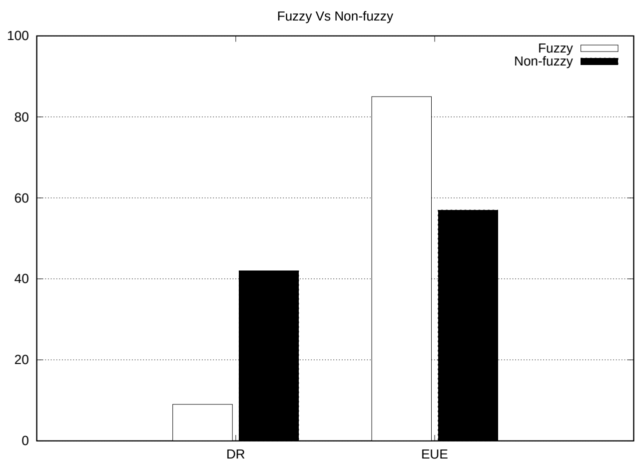

Fig. 14: Energy Utilization Efficiency

expert system to monitor the health of systems on-board an aircraft. The aim of this paper was to integrate LTspice and NS-3 simulators in order to forge a strong research collaboration between two domains (electronics and networking). The integration of these simulators were evaluated and validated by using power management use case in energy harvesting. Results based on Fuzzy control logics for power management system have shown that the integration is feasible.

The system has been designed and simulated and preliminary results have shown to be effective based on the integration between LTSpice and NS-3 simulation with the use of fuzzy control system. The Downtime Ratio and Energy Efficiency Utilization evaluation metrics were used in the simulation and the results were preferable compared to the scenario where fuzzy control was not implemented.

Acknowledgment

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