



CHOSen

Project Deliverable

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EXECUTIVE SUMMARY

This document is the final D2.2 "System Model Definition and Simulation Results", which aims to show the functional specification of the CHOSeN system models, as well as the achieved simulation results within T2.2.

Based on the whole protocol stack (from PHY to Application layer), this document reports the circuit model design and implementation, the protocol implementation and simulation, and the overall system design and implementation plan based on a common simulation framework.

The CHOSeN system has been decomposed into 2 main sub-systems:

1. RF & PHY (Circuit-Chip) level
2. Protocol (MAC, network, application) level

Each sub-system is further decomposed into a set of components, which are further separated into implementable sub-components. Each component and set of sub-components has been allocated a number of work resources covering implementation design and subsequent development activities, interface specification, sub-component integration and testing.

The performance of the components and system was analyzed regarding the requirements from WP1 and the results are presented in this document.

This detailed view of the CHOSeN system forms the overall system simulation work, helping the design process performed in WP3.





1 INTRODUCTION

This document describes the common simulation framework, the architecture of the network simulation and the implementation of the single components as well as the performance evaluation and application scenario feasibility simulations.

The simulation framework is used to assess the performance of the developed communication protocols in combination with the developed hardware components under the measured environment conditions. Standard communication protocols (IEEE802.15.4, X-MAC) were also implemented serving as a reference in the performance evaluation.

The description of the simulation framework is done top-down: from the overall setup, over the network nodes and their components (data sources, transceiver, WUR, microcontroller), and the implementation of the protocols. The models of the components, the channel model based on the measurement campaigns, and the implementation of the protocols is quite detailed in order to provide a good documentation for all partners contributing to the simulation development.

Performance evaluation has been done to show the limits of the developed hardware and protocols in the relevant environments and compare it to the limits of state-of-the art solutions.

Application scenario feasibility simulations were performed in order to guide the prototype development in WP4. These results are presented in the end of this document.

2 COMMON SIMULATION FRAMEWORK

2.1 OPNET Framework

OPNET is a simulator built on top of a discrete event system. It simulates the system behavior by modeling each event happening in the system and processes it by user-defined processes. It uses a hierarchical strategy to organize all the models to build a whole network. The hierarchy models entities from physical link transceivers, antennas, to CPU running processes to manage queues or running protocols, to devices modeled by nodes with process modules and transceivers, to network model that connects all different kinds of nodes together.

As shown in Figure 1 the network model is the highest entity and consists of node models; the node model is the subordinate tier, which consists of processors and build-in transceivers. Then, the lowest tier is the processor model.

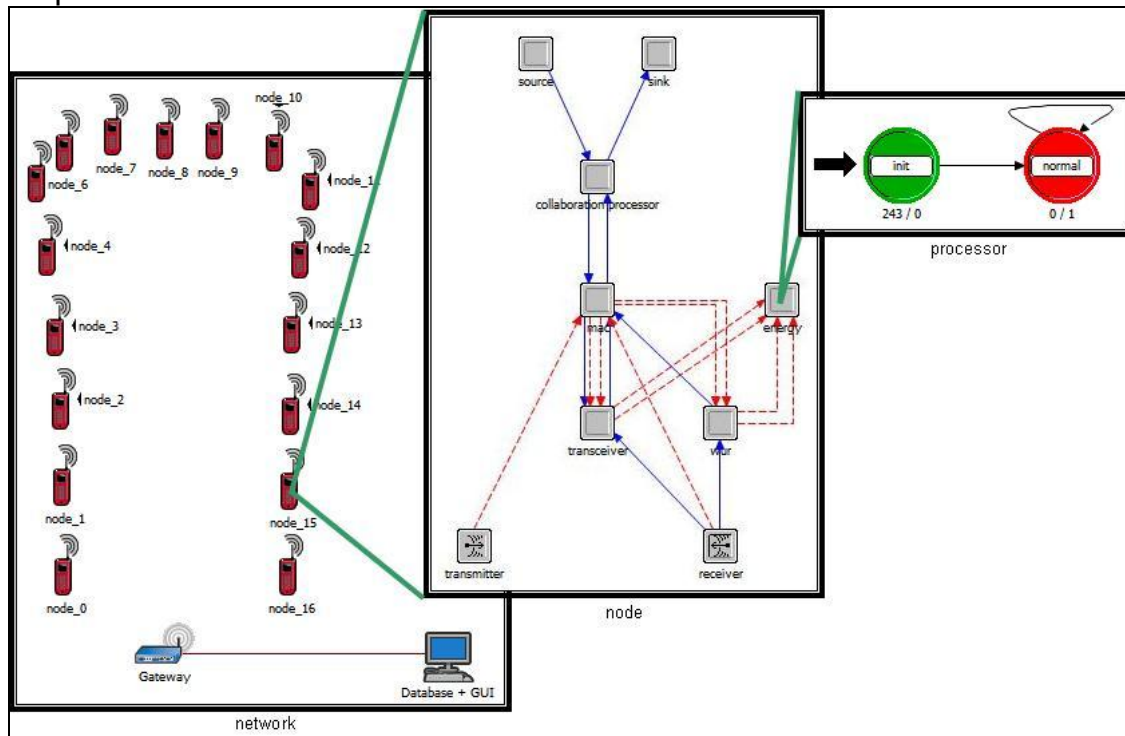


Figure 1: hierarchy of OPNET Models; network – node – processor



To simulate in OPNET, a network has to be designed, which consists of node models. These node models consist of processors, which represent the different entities of the node and are actually written in C/C++. The following chapters will specify the models, which were developed for the CHOSen simulation and how to reconfigure them.

2.2 Reconfiguration & Parameter Tuning

To ease the process of (re)configuring the simulation scenarios some methods for rapid configuration were implemented.

2.2.1 Model parameterization

The first method is model based and provides a rapid configuration tool for individual nodes. It is possible for several models to load a predefined text file at start-up to define the behavior of it. Therefore, the path to this text file has to be set in the setting dialog of the model before simulation start.

This method will be explained in more detail for the transceiver model and for the energy model.

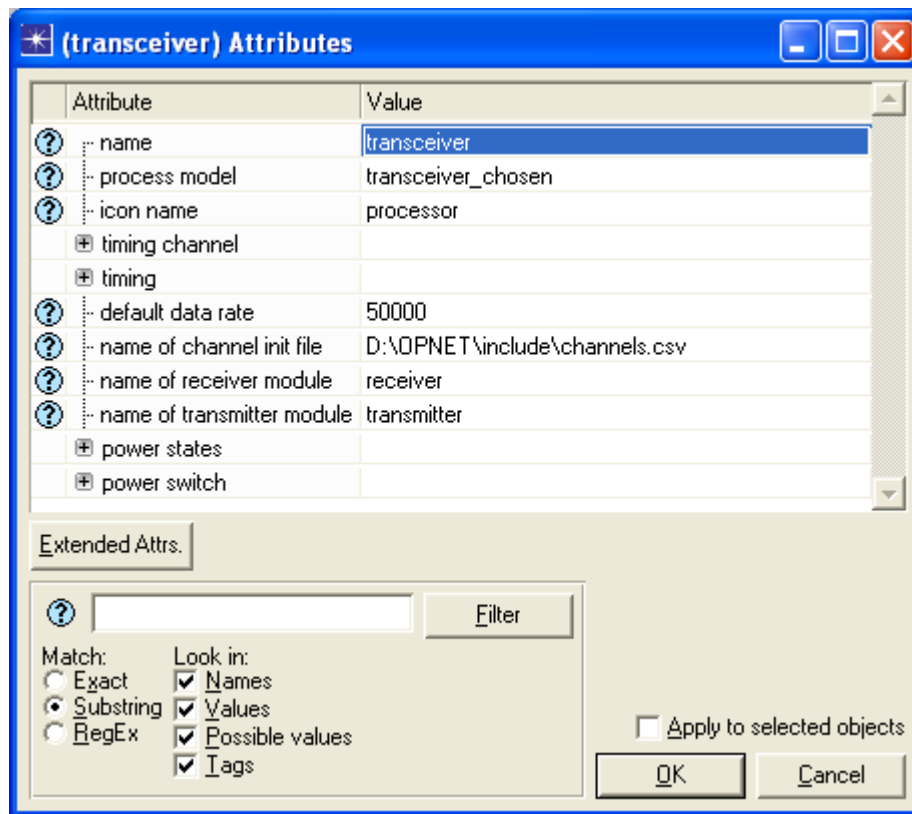


Figure 2: settings for the transceiver model

In Figure 2 you can see the setting “name of channel init file”, this setting has to be set to the path of the text file, which defines the channel parameters used for this node or alternatively has to be set to the predefined value NONE, which indicates, that no setting file shall be used at all. The setting file itself is then a comma separated list in which the channel parameters are listed. Following the same approach it is possible to set the harvesting device for the energy model. But keep in mind, that with this setting method, only the individual node can be configured rapidly; in order to configure all nodes at once and set even further simulation wide parameters a special configuration node is provided.

2.2.2 Simulation configuration

Contrary to the above a method to (re)configure the whole simulation scenario at once is provided by a special configuration node, the



“controller”. This “controller” can be seen in the top left corner of Figure 30. If this configuration node is used, it can change all parameters for all models within the simulation scenario. It even can use the model based rapid configuration methods described in chapter 2.2.1. With this, for instance, it is possible to define several transceiver description files and then simulate the same scenario with different transceivers, as done for the simulation runs in chapter 3.1 - CHOSen vs. Atmel AT86RF212. Figure 3 shows exemplarily the settings for the configuration node.

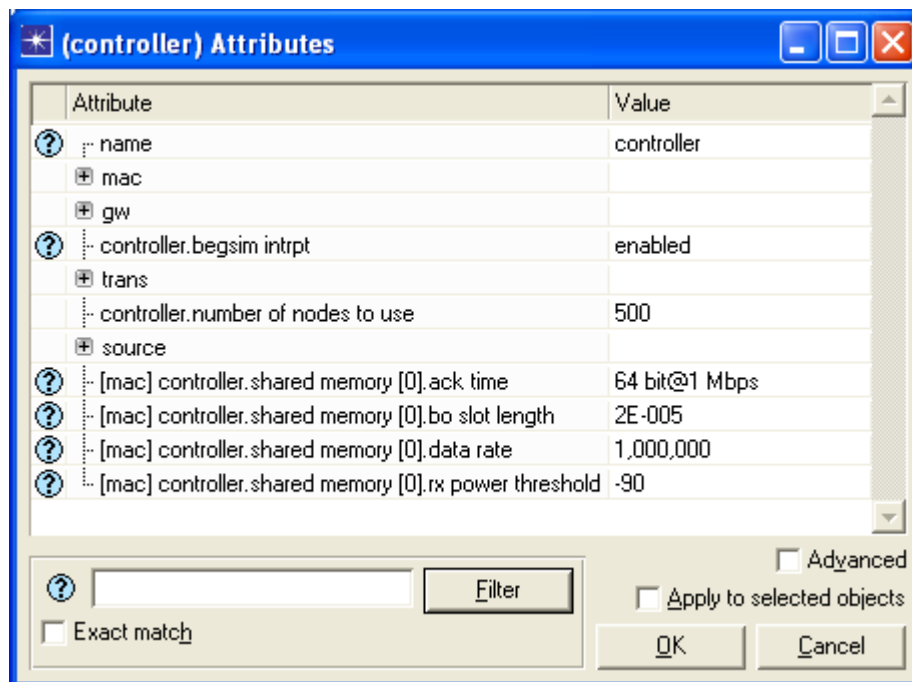


Figure 3: settings for the configuration node "controller"

As can be seen it is possible for example to set the “number of nodes to use”. So a common scenario can be created and with the configuration node, it is easy to only activate a subset of nodes within this scenario. This simplifies the scenario creation a lot, because then you don’t have to create a new scenario, if you want to use fewer nodes for your simulation. Additionally, the configuration node is structured in such a way that it is easy to implement additional setting



interfaces. With that the configuration node is ready for future simulation changes.

2.3 Channel Model

In OPNET the wireless transmission of packets between nodes is done over communication links between the transmitter processor and each receiver processor. OPNET uses a "Radio Transceiver Pipeline" to model this link. To make the link flexible for any kind of radio transmission the Radio Transceiver Pipeline consists of 14 separate stages, which are subdivided into two groups; one group for the transmitter processor and one for each receiver processor.

2.3.1 Pipeline stages

Each stage fulfils a special task in the radio link and can be changed separately.

The stages at the transmitter module are:

- Stage 0 - Receiver Group: In this stage all possible receivers will be calculated for each transmitter. This can be necessary for very large environments, such as by satellite communication. But in the CHOSen scenarios, it is applicable to neglect this stage. Therefore, to accept all receivers, but the receiver within the transmitting node, the pipeline stage "rxgroup_no_self" was written.
- Stage 1 - Transmission Delay: In this stage the transmission delay of the packet will be calculated. It is sufficient to use the build-in pipeline model "dra_txdel".
- Stage 2 - Closure: In the closure stage it will be determined, if the signal can reach a receiver at all. The build-in model "NONE" is sufficient here. With this pipeline model all transmissions might have an impact on each other.
- Stage 3 - Channel Match: In this stage it will be determined, if the transmitting and receiving channel matches. Three results are possible: the receiving packet will be treated as valid, noise, or it will be ignored. It is sufficient to use the build-in pipeline model "dra_chanmatch".
- Stage 4 - Transmission Antenna Gain: In this stage, it is possible to calculate the transmitter antenna gain in the direction of the





receiving node. Own antenna patterns can be set. For our purposes, it is sufficient to use the build-in model "dra_tagain"

- Stage 5 – Propagation Delay: The delay of the packet, caused by the propagation of the signal wave, will be calculated in this stage. The build-in model "dra_propdel" will suit here, as well.

The next 8 stages at each receiver module are:

- Stage 6 – Receiver Antenna Gain: In this stage, it is possible to calculate the receiver antenna gain in the direction of the transmitting node. Own antenna patterns can be set. Use the build-in pipeline model "dra_ragain".
- Stage 7 – Receiver Power: In this stage the received power of the signal will be calculated. A further description about the new written pipeline model "power_rayleigh" follows in the section above.
- Stage 8 – Interference Noise: In stage 8 noise from interfering packets will be accumulated. Therefore the receiving packet will be divided into different segments for each interfering packet (see chapter 2.3.2). The build-in model "dra_inoise" is sufficient for our purposes.
- Stage 9 – Background Noise: the background noise of the channel and the amplifiers etc. will be calculated here. Use the build-in model "dra_bgnoise".
- Stage 10 – Signal to Noise Ratio: For each segment of the packet the interference noise will be calculated. The build-in model "dra_snr" will suit here.
- Stage 11 – Bit Error Rate: The bit error rate for each segment will be calculated. Use the build-in model "dra_ber".
- Stage 12 – Error Allocation: the bit errors per segment will be determined. Use the build-in model "dra_err".
- Stage 13 – Error Correction: The packet is set to valid or invalid, depending on the possible bit error correction. Use the build-in model "dra_ecc".

Figure 4 shows the overview of the attributes of the transmitter and receiver.



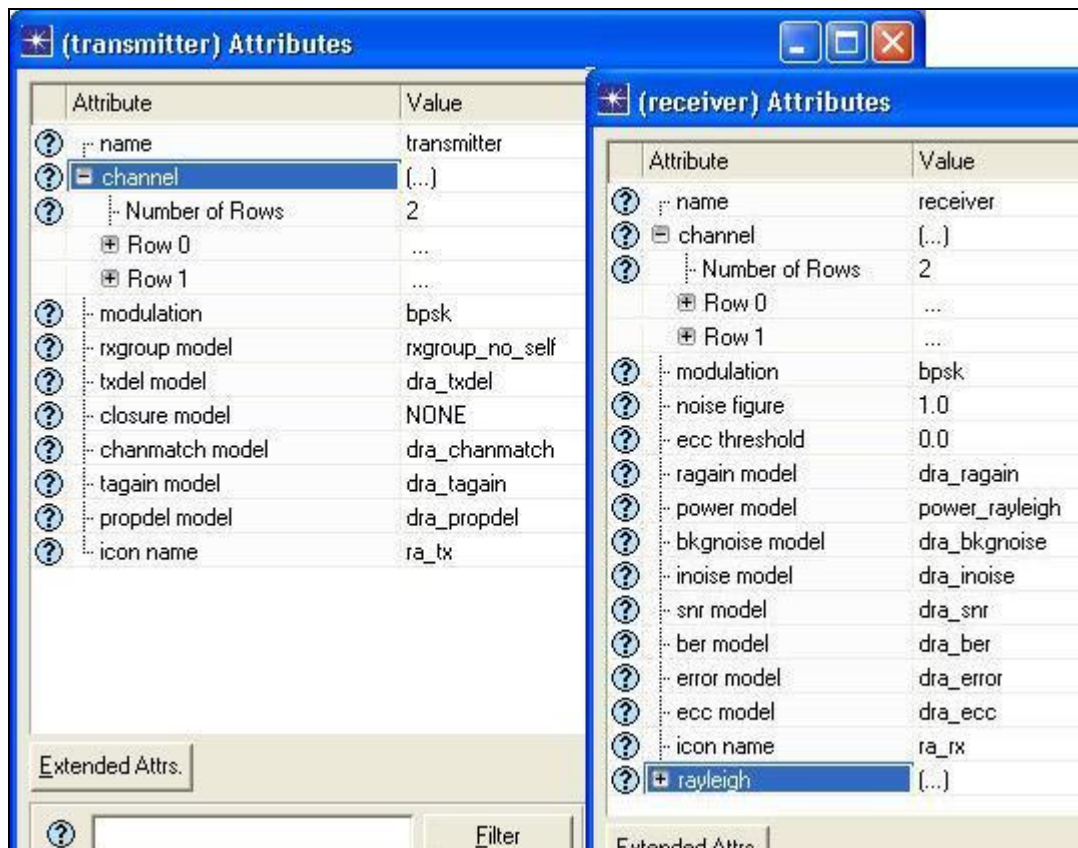


Figure 4: attributes overview of transmitter and receiver processors

2.3.1.1 Pipeline model “rxgroup_no_self”

The custom pipeline model “rxgroup_no_self” creates one great receiver group for all transmitters, but excludes the receivers in the transmitting node. Thus, the own packet will not be transmitted to the own receiver.

As well as the pipeline model “dra_rxgroup”, this model populates the state information of the receiver group channels used in the power and ecc pipeline stages to lock on a packet.

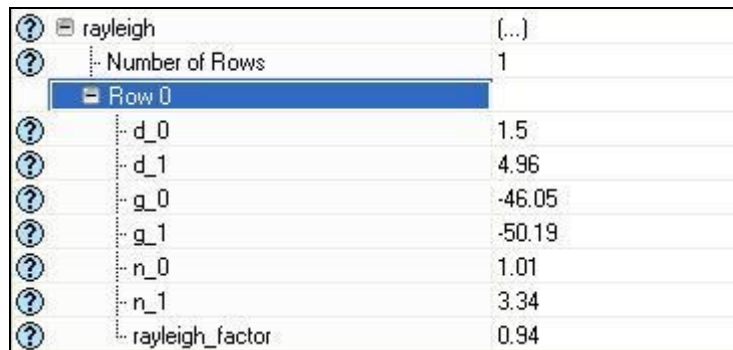
When a new packet arrives, the channel will be locked at the receiver; all packets which arrive during the reception of the locked packet will be treated as noise. After the reception is finished, the channel will be unlocked.

2.3.1.2 Pipeline model “power_rayleigh”

The custom pipeline model “power_rayleigh” calculates the signal strength at the receiver. It follows the formula described in “D21 Radio Propagation and Channel Model”.

To use this model an extended attribute has to be assigned at the receiver model:

Its name has to be “rayleigh” and its type a compound attribute. This compound attribute has 7 parameters, all of the type double. Figure 5 shows, how it should look like.



rayleigh		(...)
Number of Rows		1
Row 0		
d_0		1.5
d_1		4.96
g_0		-46.05
g_1		-50.19
n_0		1.01
n_1		3.34
rayleigh_factor		0.94

Figure 5: compound attribute “Rayleigh”

All parameters must have the same name as shown in the picture, the order of them is not important.

To use the power function without the “bend”, set “d_1” to a high value. If a failure occurs while loading the parameters, a Free-Space model will be used instead.

2.3.2 Packet segmentation

As mentioned above, if interfering packets occur during transmission, the receiving packet will be divided into segments. For each segment separately the interference noise, bit error rate and the bit errors will be determined.

Figure 6 shows two interfering packet arrivals during the transmission. In this case four sections with different interference noise levels occur; each section has to be handled separately. This means, that some pipeline stages will be called several times during the reception of a packet.

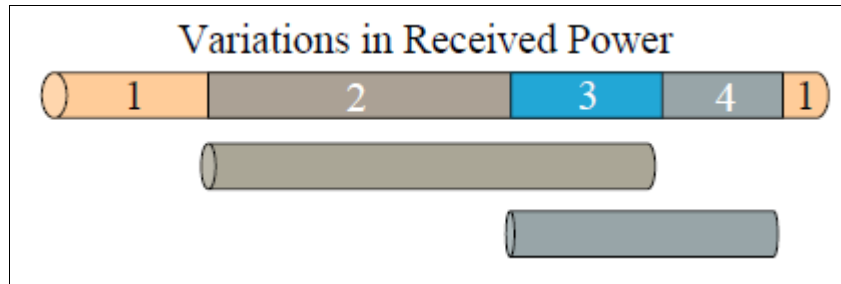


Figure 6: packet segmentation, because of interfering packets

In the end, the whole packet is marked as valid or invalid. Invalid packets will be dropped at the receiver processor; valid packets will be forwarded to the corresponding output packet stream.

2.4 Node Models

As mentioned in chapter 2.1 a node model consists of several processors, which are connected by packet streams and statistic wires. To provide a kind of interface for the processors a common node model was created.

2.4.1 Common node model

As shown in Figure 7, the processors are connected by packet streams symbolized by the blue lines and they are connected by statistic wires symbolized by the dashed red lines.

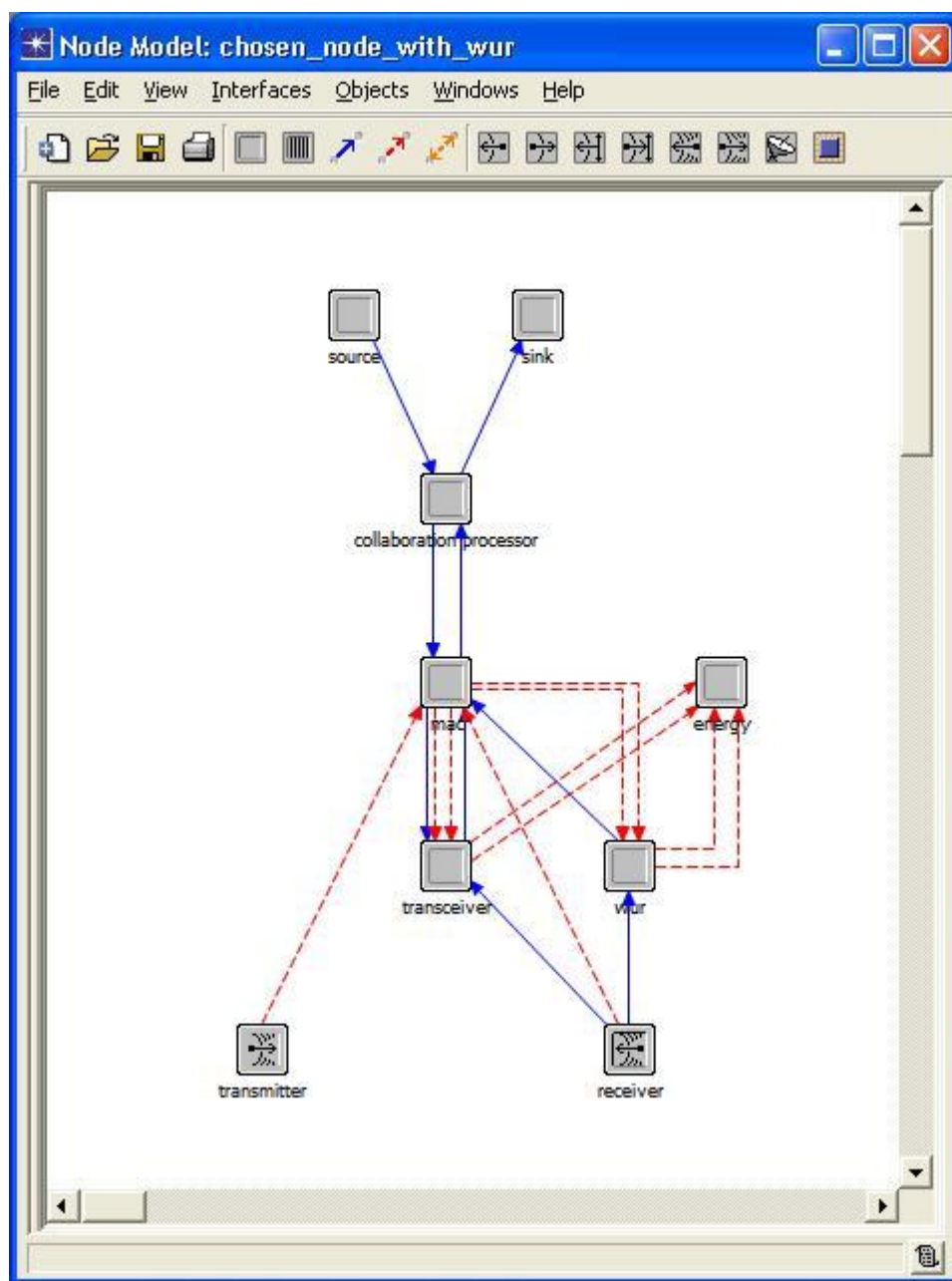


Figure 7: common node model

Packet streams are accessible to the processors over input and output ports and they present the flow of packets from one processor to

another. In contrast, statistic wires only have input ports and present the passing of information from one processor to another.

2.4.1.1 Stream interrupts

To give a common declaration of port assignment, downstream ports are connected from output port 0 to input port 0; therefore upstream ports are connected from the lowest free output port to the lowest free input port. In Figure 8 you can see as an example the connectivity of the collaboration processor.

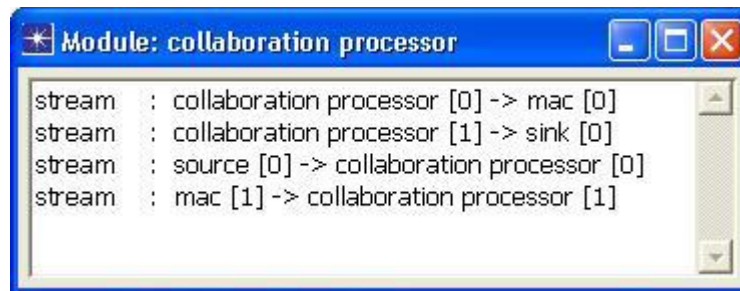


Figure 8: connectivity of collaboration processor

By starting with the downstream connections, the source output port 0 is connected to the collaboration input port 0; the collaboration processor is then connected to the mac processor again from output port 0 to input port 0. And for the upstream connection, the mac output port 1 is connected to the collaboration input port 1; but now a minor change, the collaboration output port 1 is connected to the sink input port 0, because the sink has no downstream input port.

The same changes apply for the transceiver processor. As you can see in Figure 7 the transceiver processor has no downstream output port. Therefore the stream connectivity changes again. In Figure 9 the connectivity of the transceiver processor is shown.

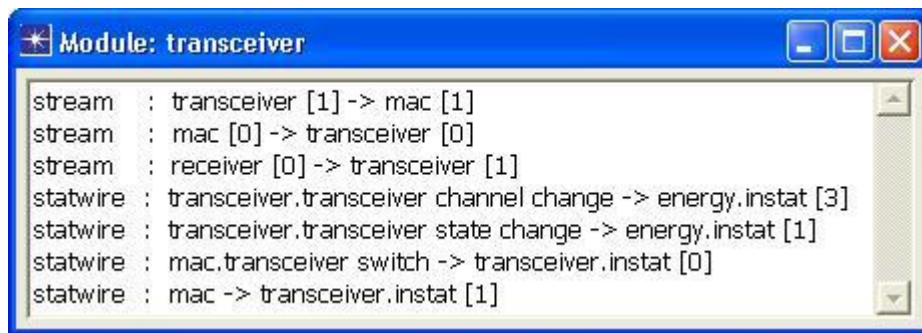


Figure 9: connectivity of transceiver processor

2.4.1.2 Statistic wires

As you can see in Figure 9 another type of connection from the transceiver processor are the statistic wires. Statistic wires don't have an output port; they only have an output statistic and an input port at the connected processor.

In contrast to packet streams, statistic wires can share a common input port, but for our purposes, different input ports are the better choice.

If a new statistic value / a new set of information is written, the statistic wire can trigger an interrupt at the connected processor. There are different strategies possible, how to do this. The first degree of freedom is, when the interrupt shall be triggered. It is possible to trigger the interrupt instantaneously, when the set of information is written – the forced mode, or the schedule the interrupt. To schedule a statistic interrupt means, to put it in the event list of OPNET. This interrupt will then occur, when it is at the head of the event list. In contrast to this, when a statistic interrupt is forced, it is triggered within the event of the processor, which writes the statistic. The second degree of freedom is under what circumstances an interrupt shall be triggered. Figure 10 shows the possible settings for a statistic wire:

- rising edge trigger
- falling edge trigger
- repeated value trigger
- zero crossing trigger
- low threshold trigger
- high threshold trigger



With these settings it is possible to control if an interrupt should occur, dependent on the value written.

src stat	transceiver state change
dest stat	instat [1]
intrpt method	scheduled
delay	0.0
rising edge trigger	enabled
falling edge trigger	enabled
repeated value trigger	disabled
zero crossing trigger	disabled
low threshold trigger	disabled
high threshold trigger	disabled

Figure 10: settings for a statistic wire

2.4.2 Middleware Node

The middleware nodes which also conduct bridging between the wireless sensor network and the CAN/AFDX busses are only modeled in the simulator in so far as they affect network behavior. In the simulation packets travelling towards the applications, end at the middleware nodes, meaning the internal busses of each demonstrator are not included.

The middleware itself is modeled as a latency distribution which incurs a certain amount of latency for each packet passing through it based on a Gaussian distribution. The reason for this approximation is that the complex hardware of the middleware nodes is very difficult to model deterministically and is outside the scope of the project. Furthermore, the middleware node models produce randomly timed commands to change the danger level of the system, thus allowing the reaction and system behavior under these conditions to be tested without having to model the entire application back-end. Finally, the middleware node models also allow for node registration and removal in order to model scalability in the simulator.





2.4.3 Generic Node

A generic node performs the data acquisition and processing tasks of the CHOSen project. These tasks are mainly performed in the application and middleware layers.

It is possible to define a set of roles that a generic node can assume by the functionalities provided by the application layer depending on the capabilities of the node:

- **SENSOR NODE:** when a node manages a set of sensors providing the sampled data to the rest of the network
- **FUSION NODE:** when a node is able to run a set of DATAFUSION computations that provide new data streams as virtual sensors
- **ACTUATOR NODE:** when a node is able to actuate a feedback mechanism that can be driven remotely.

This classification is not mutually exclusive, that means that a node may perform one or more of roles above at the same time.

2.4.4 Application Model

The application is oriented on a source-sink model. It is possible to classify the exchanged data depending on how they are originated:

- **L1 data:** Real measurements sampled by sensors.
- **L2 data:** Virtual measurements as result of data fusion operations of L1 or other L2 data.

The source-sink model requires that each kind of data stream is enumerated in order to bind a source to a sink that can effectively handle that data.

Each data stream is univocally identified as a union of:

- **DATA TYPE**, which specify the physical meaning of the data,
- **ZONE**, which specify the zone of the vehicle from which this data is sampled. This field is inherited from the node which owns the sensor.

It is important to point that the union [DATA TYPE, ZONE] must be unique, that is there must not be present two different sensors with same pair in the network.



A node must publish the list of produced streams to the middleware which will promote them when another node will require a binding to one of them.

The published and required stream may be seen as ports on the network where a service is respectively offered and used. In figure 9 the concept is exemplified.

Details about the automotive application scenario are available in the confidential version of D2.2.

2.5 Transceiver models

The switching time of a real transceiver between transmit and receive state has a big influence on the accuracy of the simulation. Also, the power consumption of the transceivers in each state will have a big influence on the overall power consumption. Therefore, a transceiver processor is implemented to represent these constraints based on the real hardware features.

2.5.1 Simulation model description

In Figure 11 the state diagram of the "transceiver_chosen" processor is shown. The transceiver is modeled with the following 7 states, which are defined as symbolic constants in the header file "transceiver_chosen.h":

- INIT
- POWER_DOWN
- DEEP_SLEEP
- SLEEP
- TX
- RCV
- SWITCH

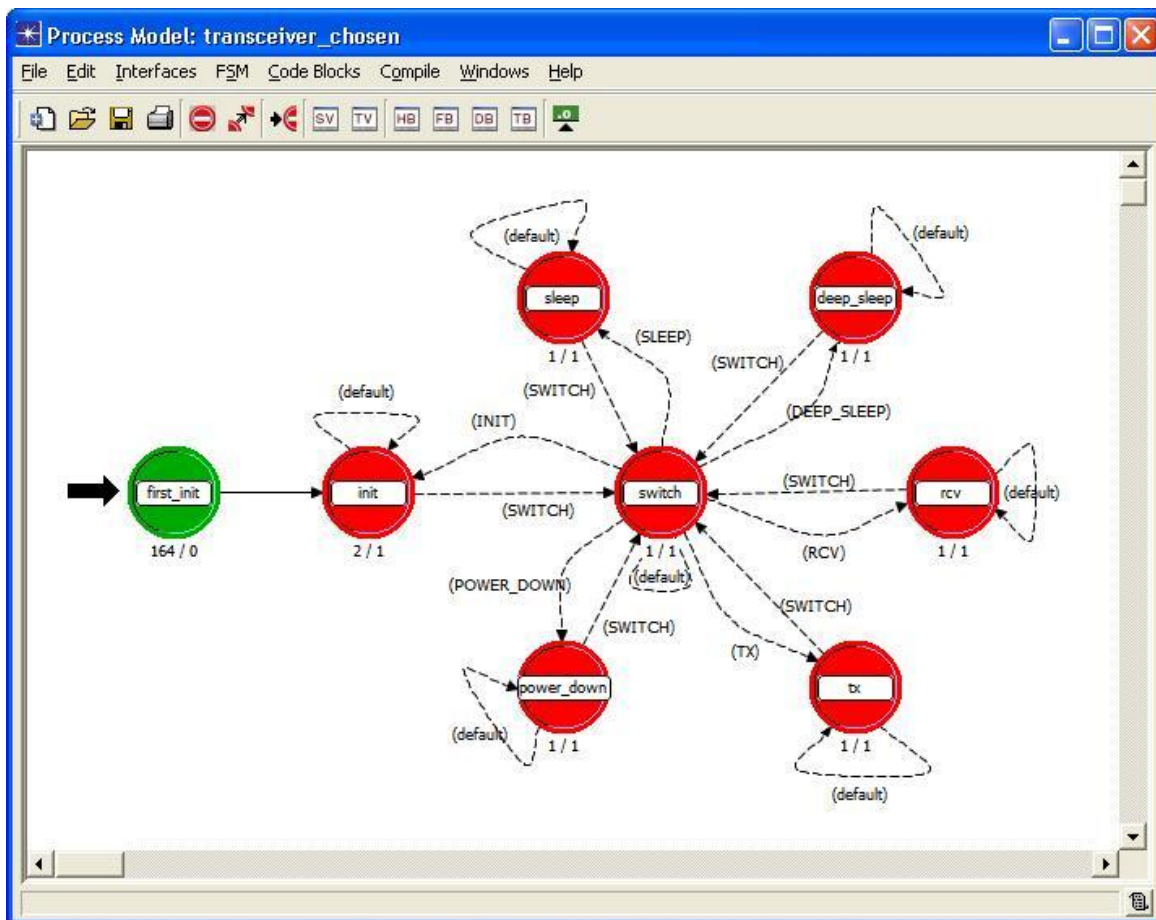


Figure 11: transceiver processor – state diagram

Each functional state has an own power consumption value, as well as a time value, which describes the time it takes to switch to other states. All these values are stored in the struct "info" defined in the header file "transceiver_chosen.h" and are transceiver attributes, which are only adjustable before the simulation starts. In order to switch a state, an interrupt has to occur at the statistic wire port 0 with the state to switch to as its value.

Because of the undefined behavior while the transceiver is switching, the SWITCH state was defined. Before the transceiver is switching to another state, it switches to the state SWITCH. While this state is active, the transceiver won't process any packets. Then, after the correct amount of time, the transceiver switches to the new state and



informs all other processors by the statistic wire "ack state change" that the switching is over.

It has to be pointed out, that the receiver only forwards packets to the upstream output port, if the transceiver state RCV is active. The same applies for the downstream; Packets will be forwarded to the transmitter, only if the receiver state TX is active. If packets arrive while the transceiver is in any other state, they will be discarded.

As can be seen in Figure 7, there are no downstream packet streams which leave the transceiver. This is due to the multi-channel capacity of the transceiver. The transceiver can be set to a specific channel over a statistic wire interrupt at port 1. This channel corresponds to the transmitter input port; downstream packets will be forwarded directly, so no downstream packet stream is necessary. While the transceiver switches the channel, the transceiver state SWITCH will be active, after the channel switch the transceiver will be in the origin state again. To make it possible for the transceiver to reach the transmitter / receiver, both names have to be set as a transceiver attribute.

To pass the power consumption info to the energy module, the transceiver has two output statistics, which have to be connected:

- transceiver state change
- transceiver channel change

Both statistic interrupts shall be scheduled interrupts. For "transceiver state change" interrupt, only the rising and falling edge triggers shall be enabled. And for the "transceiver channel change" interrupt, the repeated value trigger shall be enabled, additionally. These statistic interrupts will be called, each time, a state changes, or when a channel switch is over.

Because this transceiver model shall be capable of modeling both, the transceiver processor and the wake-up receiver (WUR) processor, the stream input port 0 is reserved for an incoming downstream packet stream. This means, that when this model represents the WUR processor, the incoming upstream packet stream has to be connected to port 1, although port 0 is free.

2.5.2 Main transceiver hardware description

Figure 12 shows the basic block diagram of the CHOSen main transceiver. A detailed description is given in Deliverable D3.3. The transceiver contains a sophisticated power management unit (PMU), which controls the multi-stage power supply. When a certain functional unit is not needed, its power supply is switched off. This concept is implemented with a very high granularity including analog as well as digital building blocks. Besides the power down mode, where everything is switched off, a very energy efficient deep sleep mode is available where an ultra-low power real time clock (RTC) is running and the content of the transceiver's configuration RAM is retained.

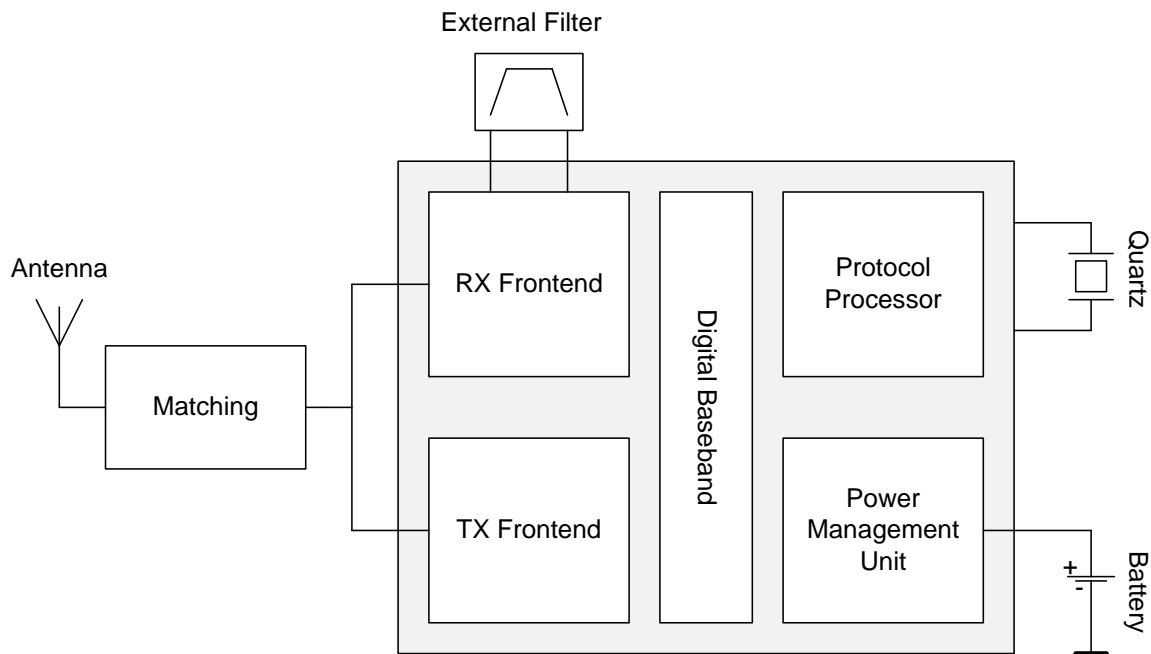


Figure 12: Block diagram of the CHOSen Transceiver



Fehler! Verweisquelle konnte nicht gefunden werden. gives an overview of the available power states together with their corresponding power consumption and the transition times from each state to its neighbors.

Details about the CHOSen transceiver are available in the confidential version of D2.2.

These states, power consumption values and transition times are used by the transceiver model in the simulation in order to ensure realistic results in the performance evaluation and application feasibility studies.

2.5.3 Wake-up receiver hardware description

The basic blocks of the WuRx are shown in Figure 15. A more detailed description of them is given in Deliverable D3.3.

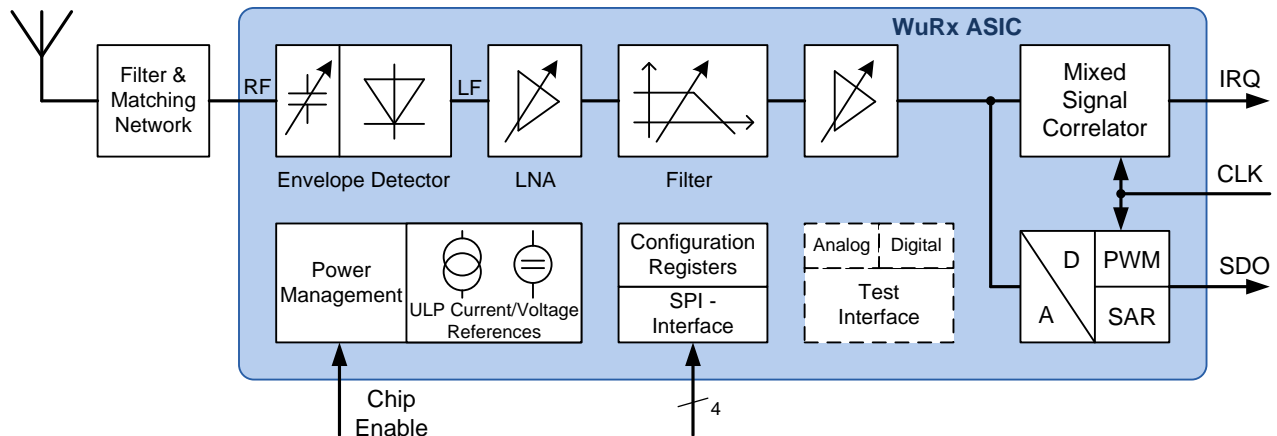


Figure 13: WuRx block diagram of first test chip

The Wake-up Receiver itself can operate in one of three power states which are illustrated in Figure 16. In active state, the WuRx is listening for incoming wake-up calls via a pattern match detection unit. In the power-save state, the configuration registers retain their contents, while in power-down state, the whole WuRx is shut down which results in the lowest power consumption, especially at elevated temperature.

Details about the CHOSen WUR are available in the confidential version of D2.2.

The values given are measurement results of the first WuRx ASIC samples that are currently under test by Technical University of Vienna.

2.6 Energy model

A main goal of the simulations is to determine the power consumption of the whole wireless sensor node since it is foreseen that some sensor nodes shall be driven by energy harvesting. Therefore an energy



module is created, which tracks the drawn energy as well as the harvested energy. The energy module processor consists of the process "energy_chosen" as the root process and of the process "sensor" as a child process of the "energy_chosen" process. In the root process "energy_chosen" all energy tracking will be done, the child process will represent the possible states of the attached sensor.

2.6.1 Root process "energy_chosen"

The root process "energy_chosen" has several attributes which define its behavior. An overview of these attributes is shown in Figure 14.

process model	energy_chosen
icon name	processor
draw update time	0.5
endsim intrpt	enabled
energy start value	0.0
harvest list file name	M:\op_models\header\harvest_list.csv
harvesting active	enabled
harvesting efficiency	0.4
own harvesting interrupt	enabled
print_vec_length	10
sensor active	enabled
sensor	
transceiver name	transceiver
wur name	wur

Figure 14: attributes of the "energy_chosen" process

The attribute "energy start value" defines the value of the available energy the process will start with. The attribute "endsim intrpt" enables the calculation of the energy value at the end of the simulation. It is preferred to enable this attribute.

As mentioned in chapter 2.5.1 the energy processor is connected to statistic wires from the transceiver processors. Following definitions are made for the statistic wire ports:

- Port 1: state change from transceiver
- Port 2: state change from wur
- Port 3: channel change from transceiver
- Port 4: channel change from wur



To handle the connected statistic wires from the transceivers, the name of the transceivers have to be set in the attributes "transceiver name" and "wur name". Then, each time a statistic wire interrupt occurs, the "energy_chosen" process will update its energy value with the drawn energy from the transceivers. If the names are not set properly, the interrupts will be ignored.

To calculate the harvested energy, the attribute "harvesting active" has to be enabled and the attribute "harvesting efficiency" has to be set accordingly.

If "harvesting active" is enabled, the "energy_chosen" process will load the external file, defined in the attribute "harvest list file name".

In this file, it is possible to define several harvest profile files and the time, when these profiles shall start. In this context a harvest profile defines the power profile of the harvesting device over time. Now, if "own harvesting interrupt" is enabled (the preferred setting) each time a new power value is available, dependent on the resolution of the profile, the process will update its energy value with the harvested energy. If "own harvesting interrupt" is disabled, the harvested energy value will be updated each time a statistic wire interrupt occurs.

Because the power management system is lossy, the "harvesting efficiency" will be multiplied with the harvested energy to represent the real harvested energy values.

To represent the drawn energy by the attached sensor, it is possible to enable a sensor with the attribute "sensor active". If the sensor is enabled, each "draw update time" the "energy_chosen" process will invoke the "sensor" process and updates its energy value with the return value – the energy drawn by the sensor. Therefore, at the beginning of the simulation the "energy_chosen" process creates a child process "sensor" which keeps track of the drawn energy by the sensor.

2.6.2 Child process "sensor"

The attributes for the child process are set at the energy processor, as well. These attributes can be seen in Figure 15.





sensor active	enabled
sensor	
sensor.invoking interrupt code	0
sensor.name list	M:\op_models\header\sensor_mode_c...
sensor.periodic mode change	disabled
sensor.power normal	0.000625
sensor.power power_down	2.5E-006
sensor.power sleep	2.5E-005
sensor.start mode	POWER_DOWN

Figure 15: attributes of the “sensor” process adjustable at the energy processor

There are several settings for the “sensor” process. The most important one is the “invoking interrupt code”; this code must match the interrupt code, the root process uses to invoke the child process. In the actual setting of both processes these values match. Then, with the setting “start mode” it is possible to define in which state the “sensor” process shall be after creating it.

As can be seen in Figure 16, the sensor process has three different states with different power values, which are adjustable also. These values are:

- NORMAL
- SLEPP
- POWER_DOWN

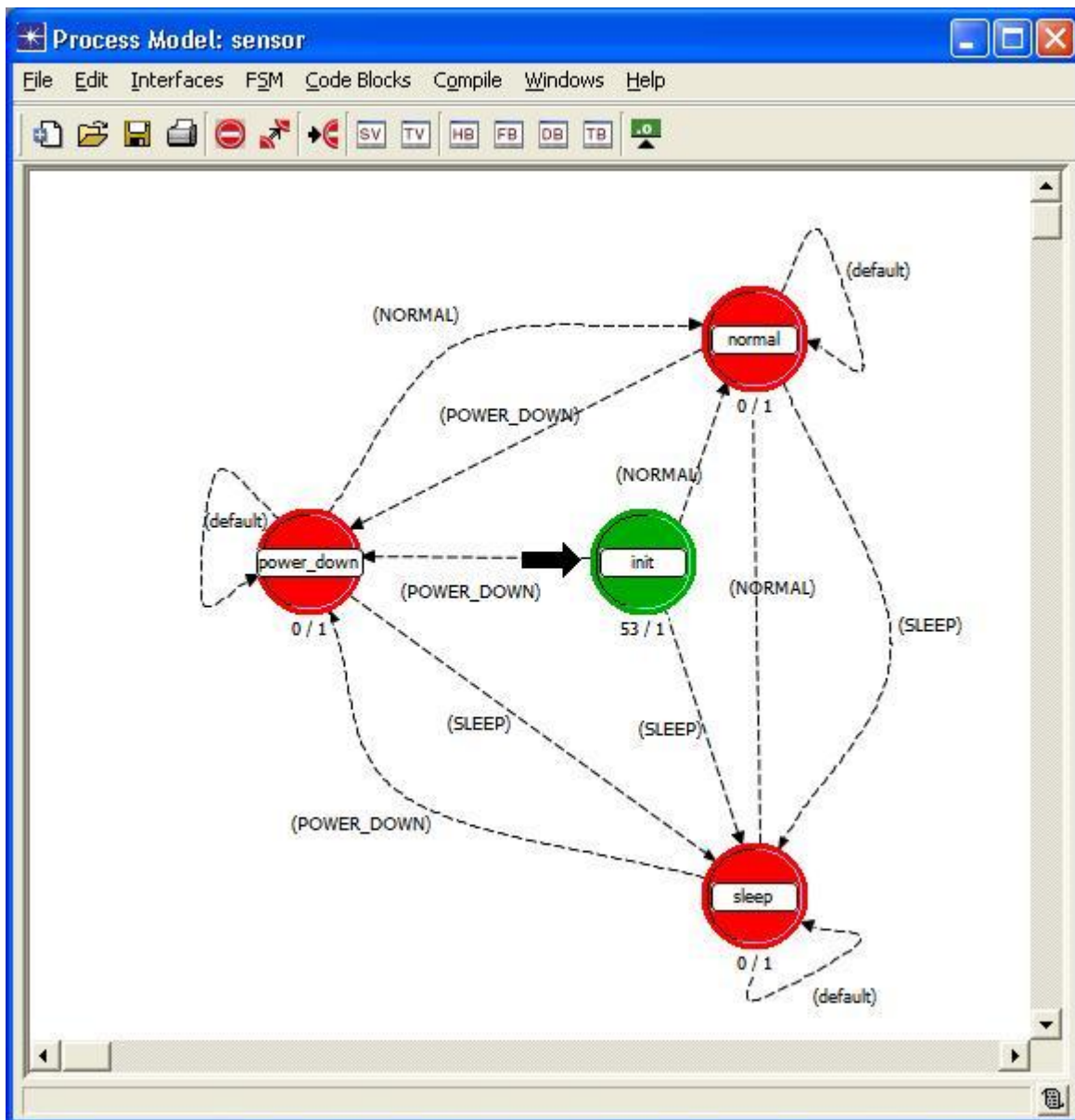


Figure 16: child process “sensor” – state diagram

The process will return different energy values, dependent on the states it was in and on the time since the last invocation.



To control the state change of the "sensor" process it loads an external file, defined by the attribute "name list". This file defines either a periodic or an event based behavior. Therefore, the attribute "periodic mode change" has to be set accordingly.

Event based behavior: An event is defined by its start time and the state to switch to. Several of these events can be defined in the list.

Periodic behavior: In contrast, a period is defined by several values; its absolute start time, the residence time for the first state, the first state, the residence time for the second state, the second state, the third state, the time after all starts again and the relative time, when this period is ended.

To clarify this, for example following values were loaded:

[1 sec, 1 sec, SLEEP, 0.5 sec, NORMAL, POWER_DOWN, 5 sec, 20 sec]

- At time 1 the period starts and the process changes to the state SLEEP
- after one second it changes to the state NORMAL
- again after 0.5 seconds it changes to the state POWER_DOWN and stays there for 3.5 seconds (5 sec – (0.5 sec + 1 sec))
- At time 5 the period starts again and changes to state SLEEP
- And so on...
- At time 21 (1 sec + 20 sec) this period ends and remains in the last active state

It is possible, to disable a state change, if the resident time is set to 0. Then this state change will just be skipped.

2.7 Medium Access Control

2.7.1 IEEE 802.15.4

In order to be able to assess the progress beyond the state of the art of the CHOSen wireless network stack and the protocols developed within the project, an evaluative 802.15.4 MAC layer has been implemented to function as a reference. The MAC is based on a repeating superframe format which begins with a beacon, followed by a





TDMA period, a CSMA period, and finally a sleep period with no activity. The MAC superframe structure is shown in Figure 17.

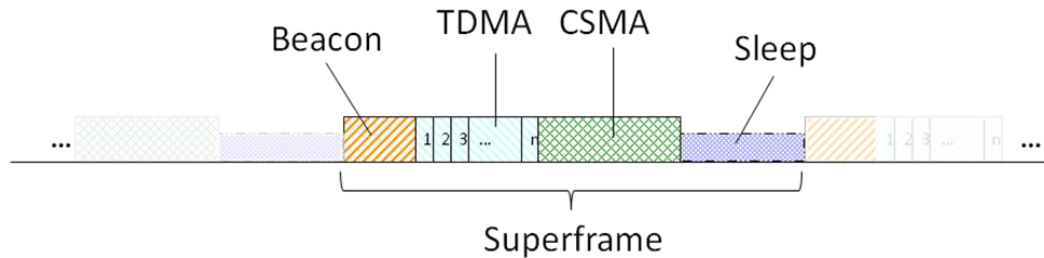


Figure 17: Protocol Diagram of the 802.15.4 Evaluation MAC

This static protocol is used to generate a statistical base-line for the evaluation of the CHOSen MAC protocols. By substituting other MAC protocols, such as X-MAC, WoR-MAC or BP-MAC for the individual frames of the 802.15.4 evaluation MAC it is possible to isolate the real effect of each of these protocols. By substituting all of them at once, the improvement of the CHOSen stack over 802.15.4 or ZigBee can be evaluated.

2.7.2 X-MAC

X-MAC is a low-power listening protocol which leverages a duty-cycled sensor node to save energy. It implements strobed preambles to reduce power consumption at the transmitting node by reducing the amount of time during which the node is transmitting. At the same time it uses addressed preambles to reduce losses due to overhearing at other nodes in range which are not the designated target node. Thirdly, it uses an ACKed preamble which allows the target node to end a preamble sequence prematurely and further conserve energy reserves.

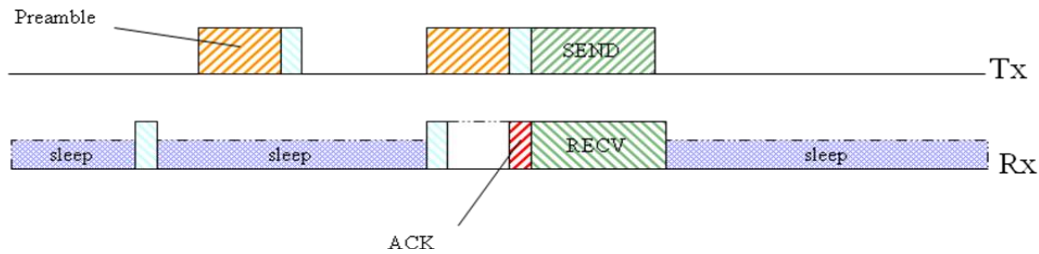


Figure 18: Protocol Diagram of X-MAC Behavior

The X-MAC protocol behavior is shown in Figure 18. This protocol has been implemented in the simulation environment and is used to further augment the 802.15.4 stack and give a further state-of-the-art benchmark for evaluating the effects of WoR-MAC on system behavior. A screen shot of the automata which defines the protocol in the simulation environment is displayed in Figure 19.

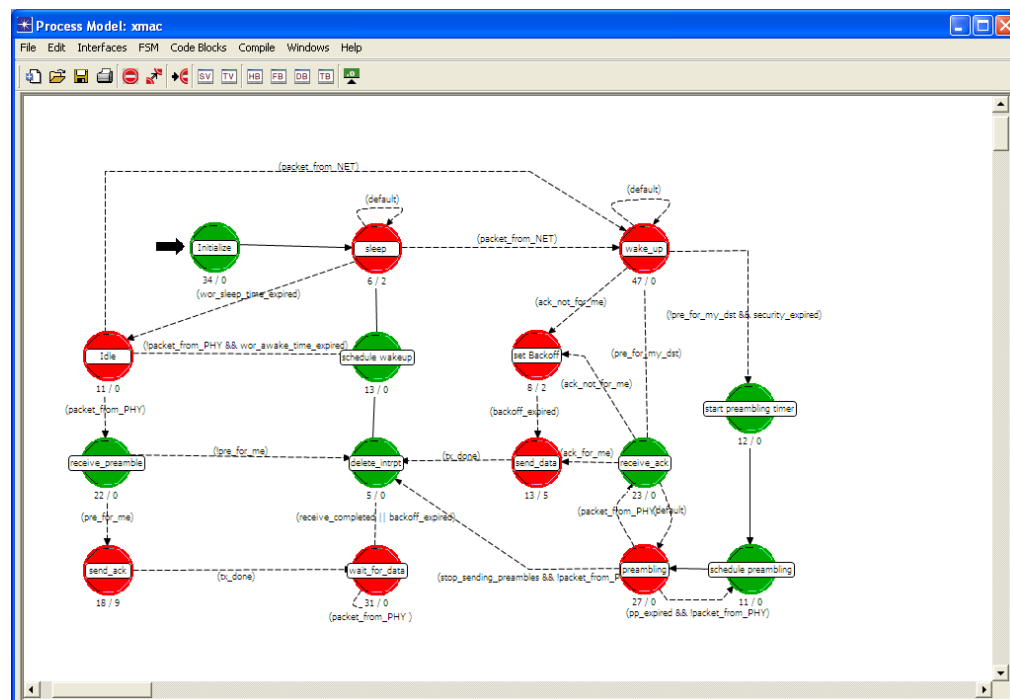


Figure 19: X-MAC Process Model from the Simulation Environment

2.7.3 WoR-MAC

The behavior of the WoR-MAC is detailed in Figure 20 which shows how single addressed wake-up preambles affect a grouped cluster. It also demonstrates how missed preambles are handled by the system where preambles are repeated until a certain threshold is reached and the system continues and begins communication.

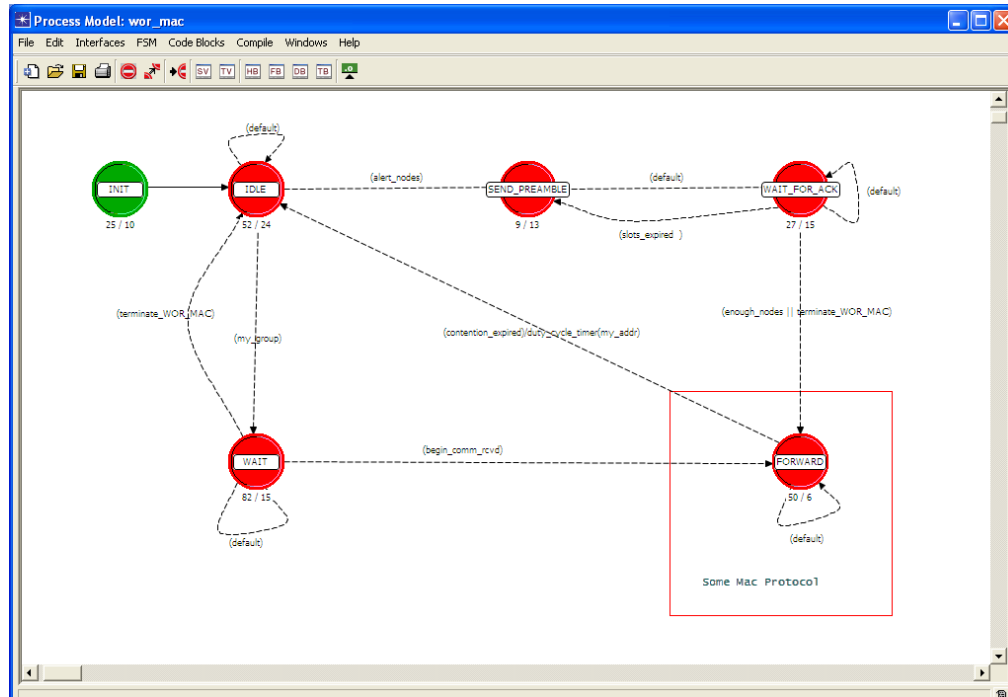


Figure 20: WoR-MAC Process Model from the Simulation Environment

Currently, the protocol design phase has been completed and the protocol has been implemented in the CHOSen OPNET simulation environment. The protocol has also been integrated with the transceiver, wake-up receiver and energy model in the simulation environment (see Figure 7). It has also been implemented for evaluation purposes on proprietary test hardware in the laboratory at the Karlsruhe Institute for Technology and is currently being tested.

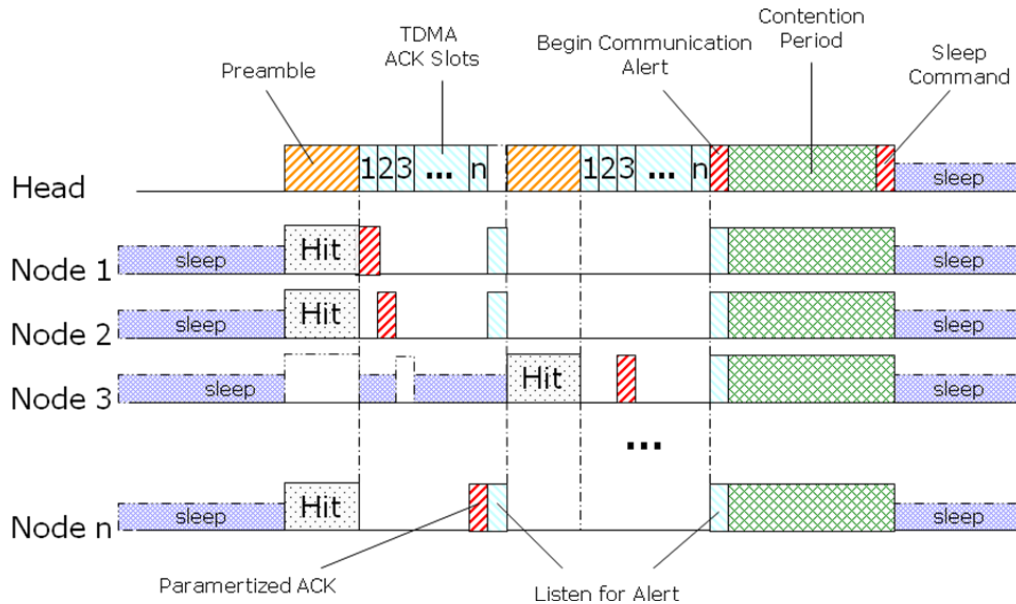


Figure 21: Protocol Diagram of WoR-MAC Behavior in a Cluster

2.7.4 BP-MAC

Another MAC protocol is the BP-MAC protocol¹, already presented in WP2 of the first review.

¹ A. Klein, J. Klaue, and J. Schalk, "BP-MAC: A High Reliable Backoff Preamble MAC Protocol for Wireless Sensor Networks", EJSE, Special Issue: Sensor Network on Building Monitoring: from Theory to Real Application, 2009

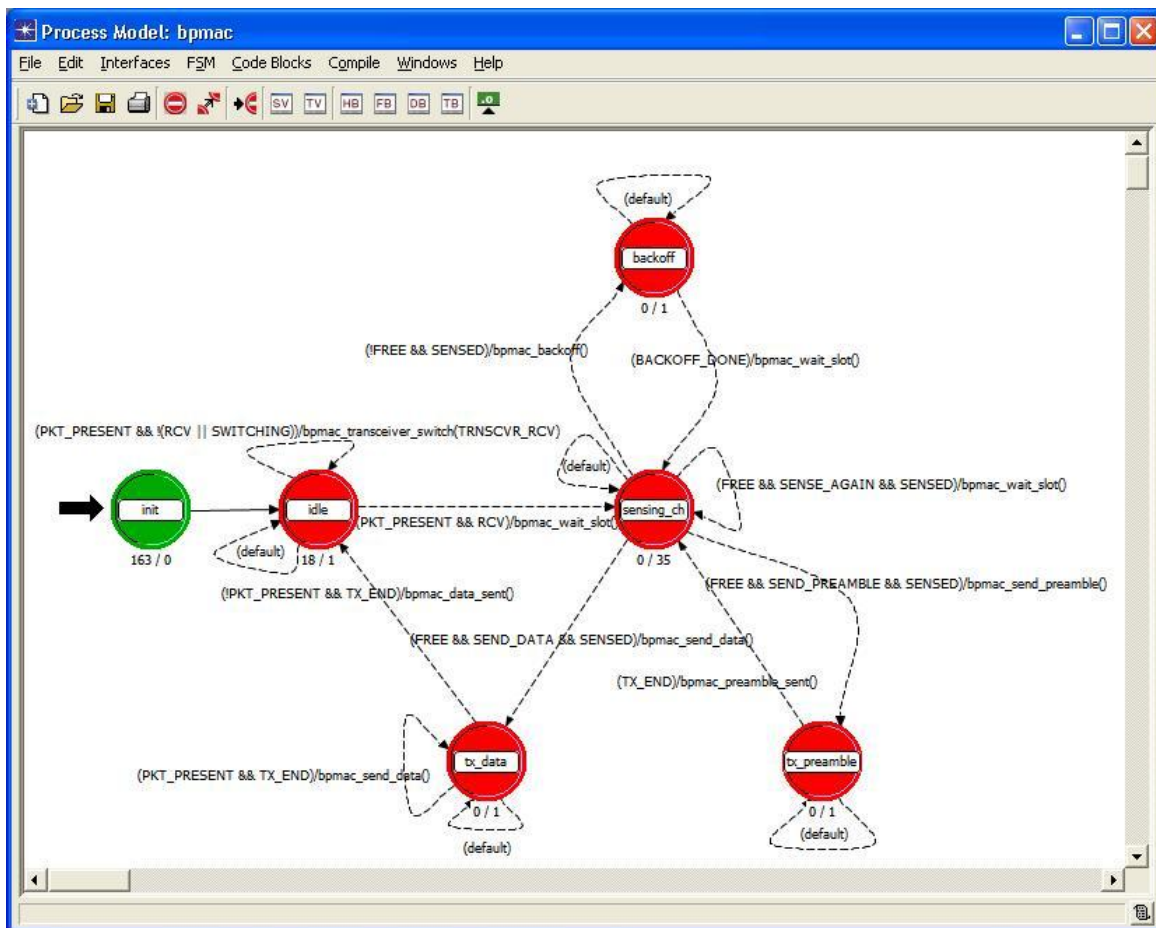


Figure 22: "bpmac" processor - state diagram

In short form, the BP-Mac is a kind of CSMA/CA scheme, but instead of backing off quietly, it sends back-off preambles to contend for the channel. The node which sends the longest preamble, wins the channel; Figure 22 shows the state diagram of the "bpmac" processor and Figure 23 shows the contention for the channel with three nodes.

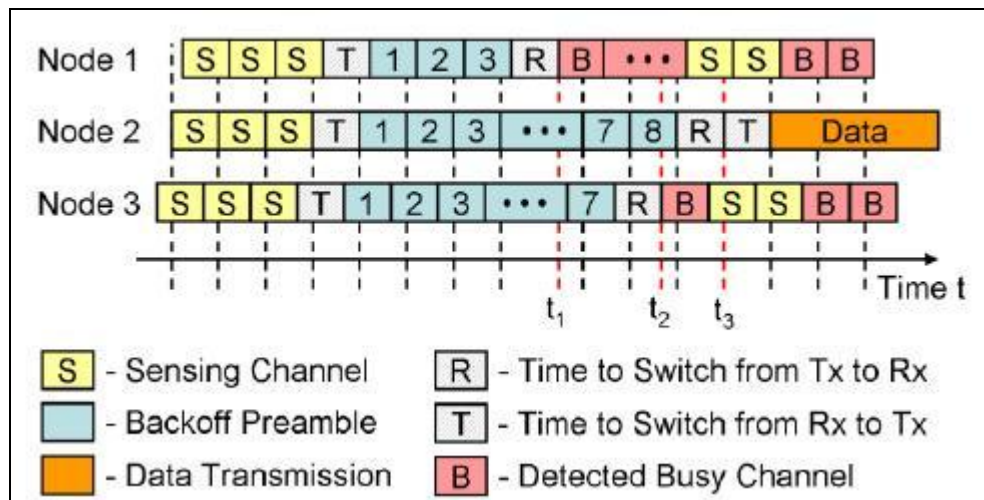


Figure 23: three nodes contend for the channel using BP-Mac²

As depicted in Figure 23 a node has to listen three times, before it is allowed to start sending its back-off preamble. This is necessary, because of the time it takes a transceiver to switch from transmit to receive mode and vice versa. If the initial sensing of the channel is longer than the switching time, it is more probable for a node to detect a busy channel. Therefore the three times listening is implemented.

2.8 Collaboration protocols / Data Fusion

2.8.1 Message format

The communication between application and middleware consists in a set of 5 messages encapsulated in a generic transport frame.

They are identified through a 3 bits long header that contains the type information.

The available messages are:

- Publish message (type=0)

² Picture from A. Klein, J. Klaue, and J. Schalk, "BP-MAC: A High Reliable Backoff Preamble MAC Protocol for Wireless Sensor Networks", EJSE, Special Issue: Sensor Network on Building Monitoring: from Theory to Real Application, 2009



- Demand message (type=1)
- Subscribe message (type=2)
- Data message (type=3)

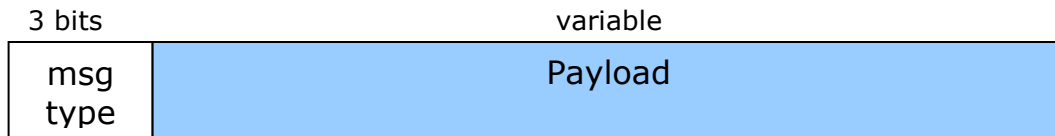


Figure 24: Generic Message frame format

- Control message (type=4)
- Considering the variable length of the fields, it has been chosen to adopt the formatted packet in order to define the fields and the size of a packet directly from the proto-C code.

Publish message

In this message the application declares the streams that it provides (outputs). Streams are defined only by DATA TYPE because they are under the same ZONE of the sensor. The zone is also declared in a 6

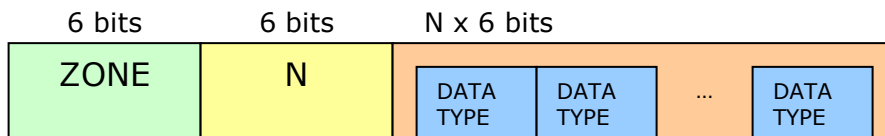


Figure 25: Publish Message format

bits field. The field n declares the number of following stream IDs.

Demand message

In this message the application requests the streams that it needs (inputs) for DATAFUSION or monitoring purposes. Streams are defined





by DATA TYPE and ZONE because they are can be originated in several zones of the vehicles by different nodes. The field n declares the number of following unions [DATA TYPE,ZONE].

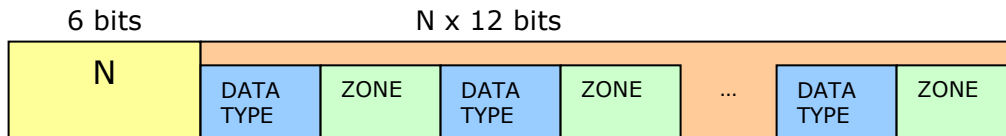


Figure 26: Demand Message format

Subscribe message

With this message, the middleware subscribe itself to the application for a list of data streams that has been remotely requested by other nodes. The data streams are listed into a list of DATA TYPE. Zone is implicit and is the one set into the Application layer and that was communicated in the Publish message. The field N indicates the number of the following elements.

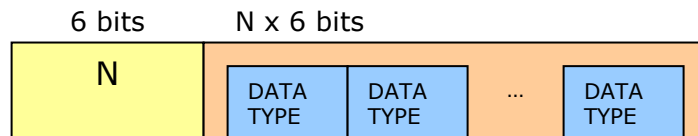


Figure 27: Subscribe Message format

Data message

This message is sent from the application to the middleware every time some data stream has been subscribed by the middleware.

Moreover, it is also used when a remote data arrives at middleware and need to be notified to the application.

- **Node status:** it contains the value of the status register of the sender node. It can have one of the following values:
 - MONITORING STATUS (0)
 - SAFE STATUS (1)
 - ACTIVE STATUS (2)
 - DANGEROUS (3)
 - INACTIVE (-1) only for simulation
 - ERROR (-2) only for simulation
- **ZONE:** it indicates the zone of which the sender node belongs.
- **DATA TYPE:** it is the DATA TYPE that together the zone allows to identify the stream univocally.
- **Value:** it is the value of the data. Its length depends from the DATA TYPE.
- **Counter:** it contains the sequence number of the data that is used to check the coherence of the flow.

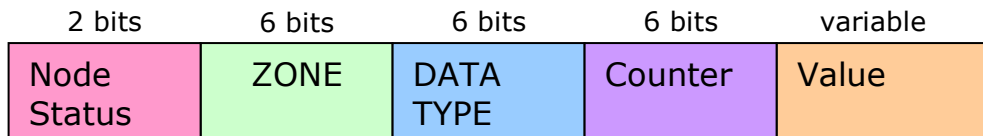


Figure 28: Data Message format

Control message

This message is sent from CENTRAL NODE to all the nodes in broadcast. This message is sent periodically and after a danger state condition is detected. The status network field contains the status of the network, maintained by the central node, which must be adopted also by other nodes as soon as they can. The following fields contain information for the actuators that must be activated in several cases with different parameters.

- Network status: it contains the network state that must be adopted by the receiving node.
- Actuator status: it contains the level of attention that must be given to the driver by the actuator.
- Time to Collision (TTC): it contains the last time to collision estimate done by the CENTRAL NODE
- Distance to Collision (DTC): it contains the last distance to collision estimate done by the CENTRAL NODE
- TEXT ID: contains the code of a preset warning message

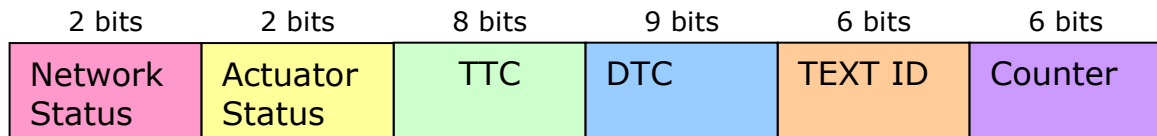


Figure 29: Control Message format

- Counter: it contains the sequence number of the data that is used to check the coherence of the flow.

2.8.2 Data Fusion

Details about the automotive application scenario are available in the confidential version of D2.2.

3 SIMULATIONS RESULTS AND PERFORMANCE EVALUATION

The results section is separated into two parts: performance evaluation regarding the limits of the system in terms of throughput, latency, loss, energy consumption and number of supported wireless data sources, and application scenario feasibility in terms of performance of the implemented application scenarios regarding the requirements.

In sections 3.1 and 3.2 the results of the performance evaluation regarding the limits of the system are shown, while Section 3.3 shows the results of the performance evaluation of the application scenarios regarding their requirements.

3.1 CHOSen vs. Atmel AT86RF212

In order to evaluate the performance of the CHOSen node and to outline typical simulation behavior, we compared the CHOSen node





with a node that uses the Atmel AT86RF212 as its transceiver. The Atmel212 is chosen, because this transceiver is operating in the 868 kHz band and has some low power modes available as well. Therefore following setup is created.

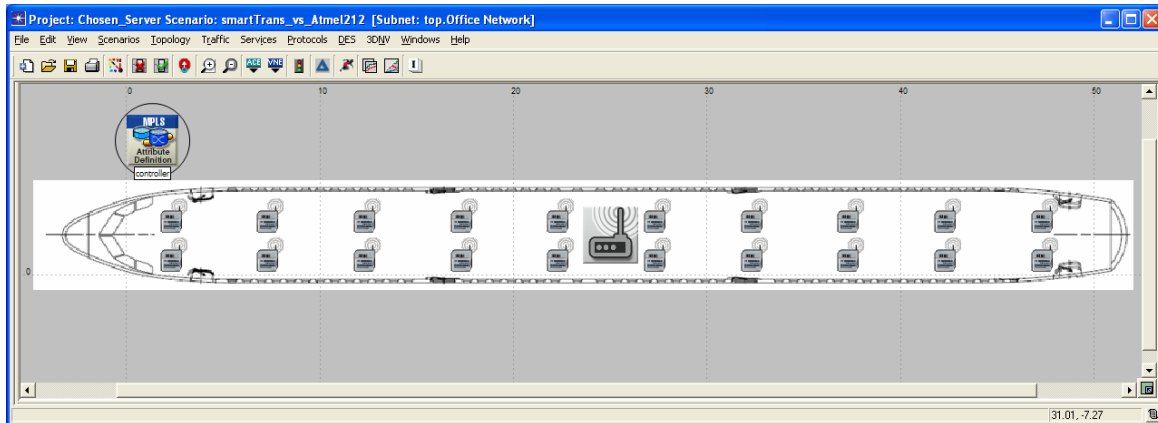


Figure 30: Simulation scenario for CHOSen vs. Atmel212

Figure 30 shows the network scenario for this comparing simulation. 20 sensor nodes are distributed over the aircraft cabin. In the middle of the aircraft the access point is located and receives all the traffic of the nodes. Thereby the nodes are transmitting with 10dBm and it is possible for them to reach the access point with sufficient SNR to maintain a communication according to the channel model obtained by the measurement campaign. The CHOSen nodes have their WuRx enabled in active listening mode and its transceiver in power down mode. In contrast to that the Atmel212 will be duty cycled for saving energy. Thereby, within a duty cycle the transceiver is always 48 ms in RCV mode to listen for the beacon. Following figure gives an overview of the proportion of power consumption per duty cycle. Exemplary a cycle of 10 seconds is chosen, which leads to a maximum wake-up delay from 10 sec.

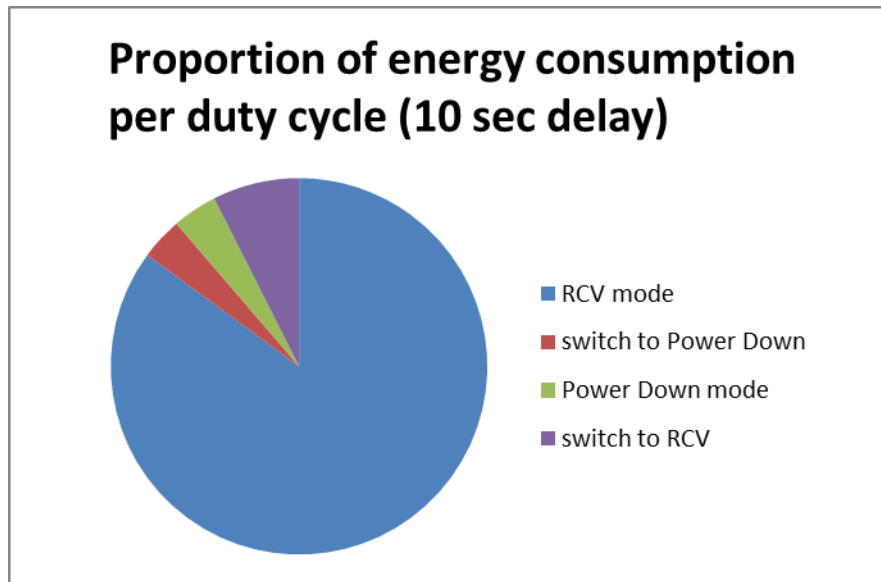


Figure 31: proportion of energy consumption per duty cycle

As shown in is that even with a duty cycle of 0.048% - 48 ms / 10 sec – the main energy consumption is during RCV mode and, in this case one cycle yields to approximately 0.156 mJ. In both simulation scenarios, after 12 hours of flight the access point sends a beacon to indicate to the nodes that they shall start transmitting their stored data. For the MAC scheme a simple acked CSMA is used. The CSMA phase for a node is defined as finished, when the ack for its packet arrives.

Keep in mind, that this scenario is deliberately that simple to have a good basis to compare both nodes. Following figure show the overview of the available power states together with their corresponding power consumption and the transition times from each state to its neighbors for the Atmel212.

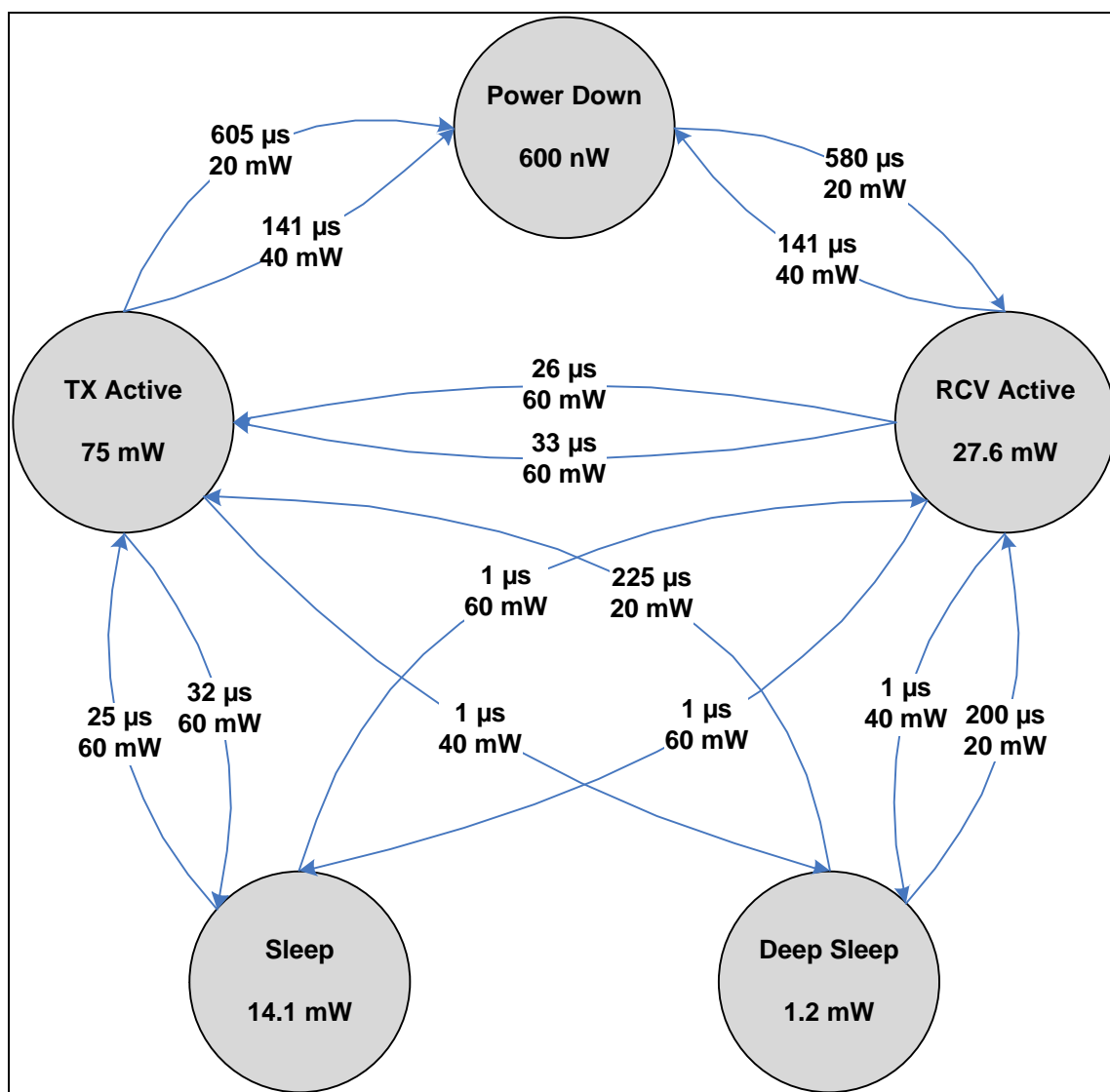


Figure 32: state diagram for the Atmel212³

³ Specifications according to Atmel212 data sheet:
(http://www.atmel.com/dyn/resources/prod_documents/doc8168.pdf)



According to the specifications for the Atmel212 the data rate is 40 kbps contrary to the transceiver on the CHOSen node with 50 kbps. As mentioned above all nodes start the CSMA process after 12 hours of flight and want to transmit one packet each with a packet size of 200 bit and an ack size of 64 bit. This leads to a network load of 8% for the CHOSen node and 10% for the Atmel212. Due to the fact that for this scenario it is possible for all nodes to reach the access point with a sufficient receiving power, mainly all transmission failures originate from collisions.

The reference values will be the energy consumption and the maximum delivery delay. The following figure shows the composition of the total energy consumption for the CHOSen node.

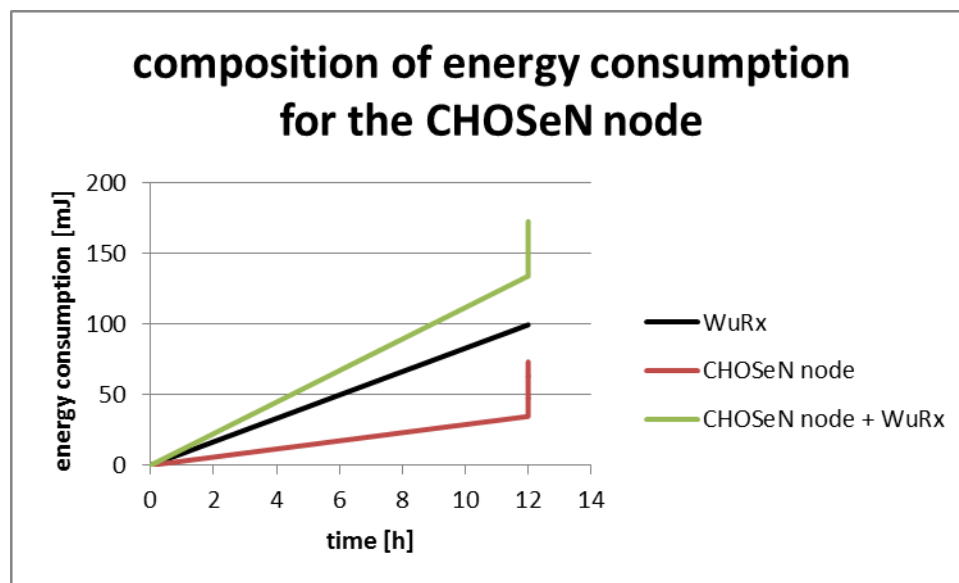


Figure 33: composition of energy consumption for the CHOSen node

In

Figure 33 it can be seen, that the total energy consumption – the green line – consists of the drawn energy by the transceiver (here the new



smartTrans) and the drawn energy by the WuRx.⁴ The WuRx has constant energy consumption, because it is always in active listening mode. Due to the fact, that the main transceiver is most of the time in power down mode, its energy consumption can be even lower, than the consumption of the WuRx. As can be seen further, the switching times between different transceiver states are important, because they are mainly responsible for collisions. With increasing switching time the probability that the clear channel access (CCA) mechanism fails increases as well and this leads to collisions.

To illustrate this further Figure 34 shows the energy consumption during the CSMA phase. Different to Figure 37, these values are not a system average, but they are values for one specific node out of one simulation run. For both scenarios the “most unfortunate”⁵ node was chosen.

⁴ For ease of comparison all other sources of energy consumption are neglected. Mainly these two sources will provide the highest consumption, anyway.

⁵ “most unfortunate” in the meaning of energy consumption, so the node with the highest energy consumption was chosen

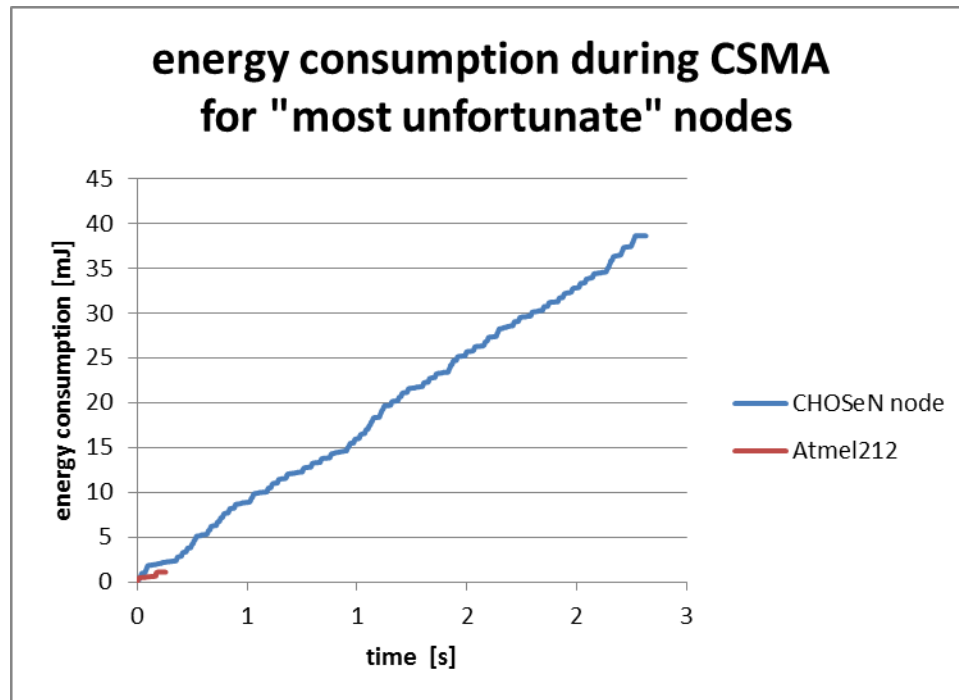


Figure 34: energy consumption during CSMA for “most unfortunate” nodes

The graphs are normalized at the beginning of the CSMA phase, so both start at time zero with zero energy consumption. As can be seen, after start of the CSMA phase the graph for the Atmel212 ends earlier than the graph for the CHOSen node. Because of the longer switching times of the transceiver used in the CHOSen nodes there are more collisions in the system. From this it follows that more retransmissions are needed and the whole CSMA phase gets longer.

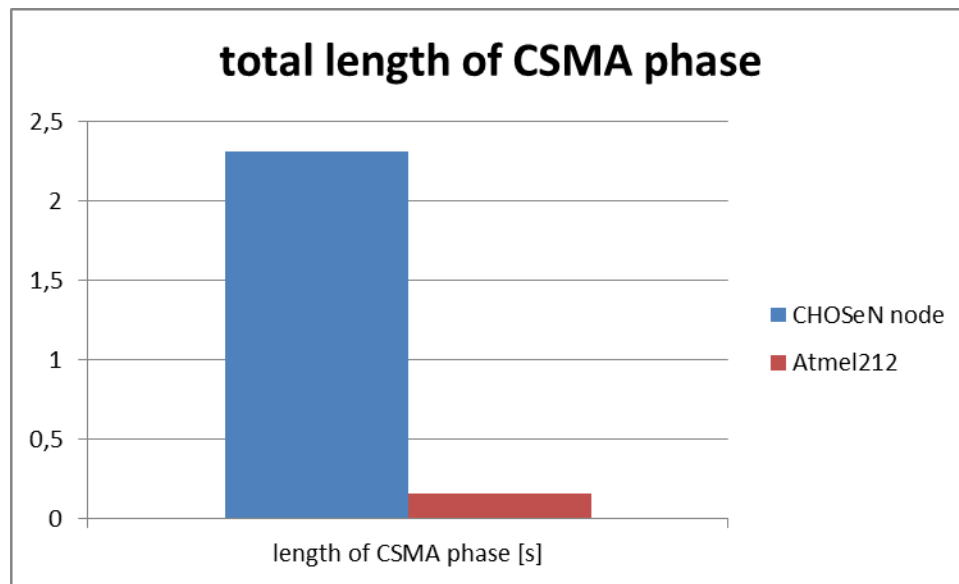


Figure 35: total length of CSMA phase

Figure 35 shows the total time it takes to send all packets to the access point. It can be seen, that despite the 20% lower bitrate of the Atmel212 roughly 6.8% of the time is needed to transmit all packets. As already mentioned this is mainly due to the higher collision probability when the rx/tx switching time is higher.

This fact can be seen in Figure 36 as well, which shows the energy consumption values for the CSMA phase. Each large peak corresponds with the (re)transmitting of the packet. From this follows directly that in this case the Atmel212 needed two (re)transmissions and the CHOSen node needed lots more. Again these graphs are taken out of a single simulation run and therefore are not representative - they are shown only for clarification. Additionally CSMA might not be a good solution for this scenario, but is chosen due to its simplicity for comparison purposes only.

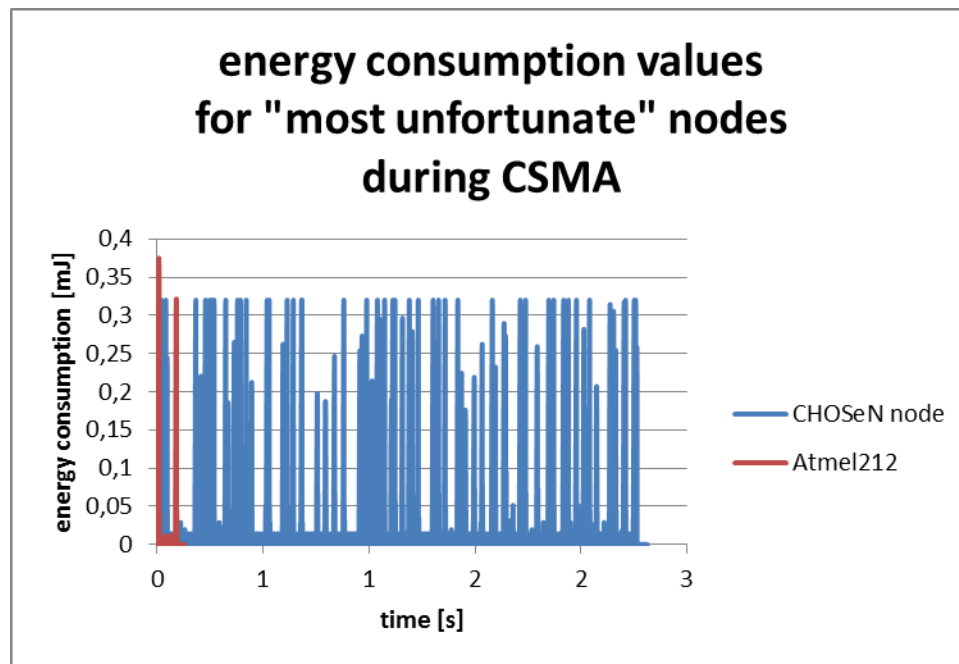


Figure 36: energy consumption values for "most unfortunate" nodes during CSMA

Figure 37 shows now the total energy consumption per node – in the case of the Atmel a duty cycle of 0.48% is chosen. The graph for the CHOSen node is a system average. So it's the energy consumption for the whole system divided by the number of nodes within the system.

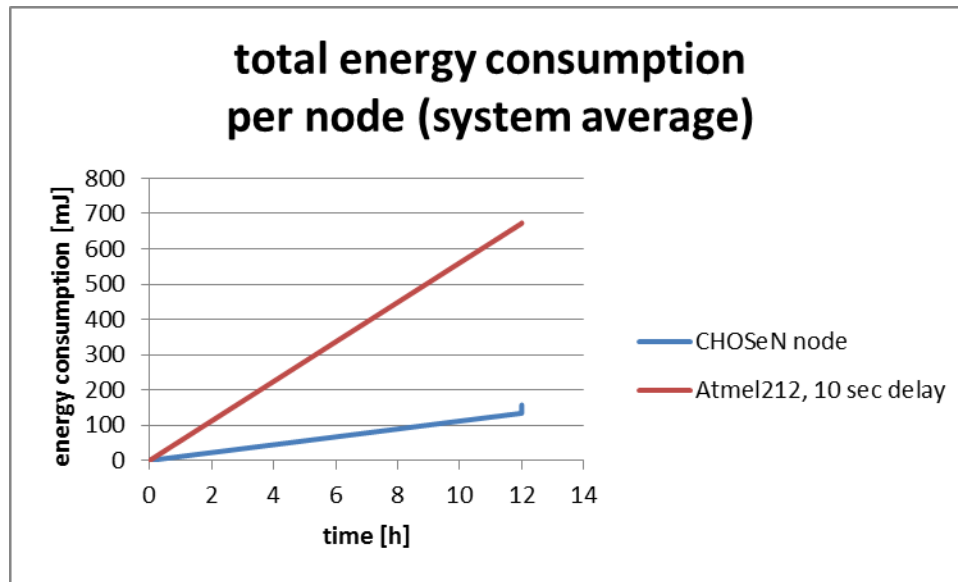


Figure 37: total energy consumption per node - system average

The CHOSen node has a lower energy consumption comparing to the Atmel212, after 12 h the difference is about 516 mJ.

To have a better feeling for the impact of the duty cycling Figure 38 shows the consumed energy against the delay which is introduced by the wake-up process – either the WuRx or the duty cycling.

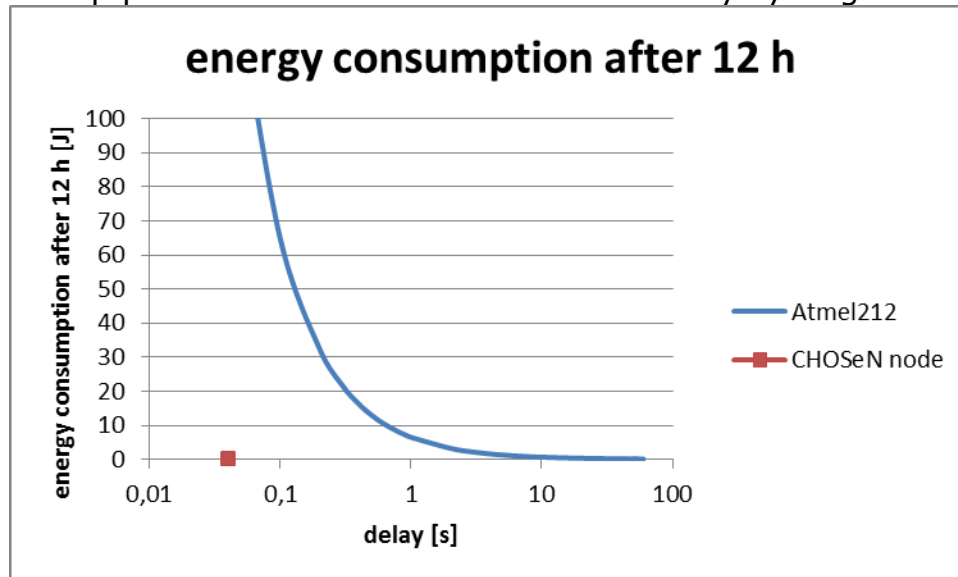


Figure 38: energy consumption after 12 h against wake-up delay



It can be seen, that the CHOSen node outperforms the duty cycled Atmel212 system by far.

3.2 Performance WorMAC versus X-MAC

The performance of WoR-MAC was evaluated using the following metrics as a function of the number of nodes in the network:

Packet Success Ratio The packet success ratio is defined as the number of packets recognized by the receiver on the sink node, divided by the number of packets sent by all nodes in the cluster. The main reason for lost packets is collisions on the channel and noise resulting in bit errors during transmission.

Transmission Delay We define transmission delay as the time between the start of the communication period until the packet is received at the sink. This excludes the time, where the packet is stored during the flight and only accounts for the delay added by the protocol. The values shown here are the averages of all packets during a single simulation run with a fixed number of nodes and a specific protocol.

Energy Consumption The energy consumption represents the electrical energy spent by each node during the complete simulated time. Only the power consumed by the transceiver is considered, since the utilization of the other parts of the sensor node is nearly identical for all protocols.

3.2.1 Delay



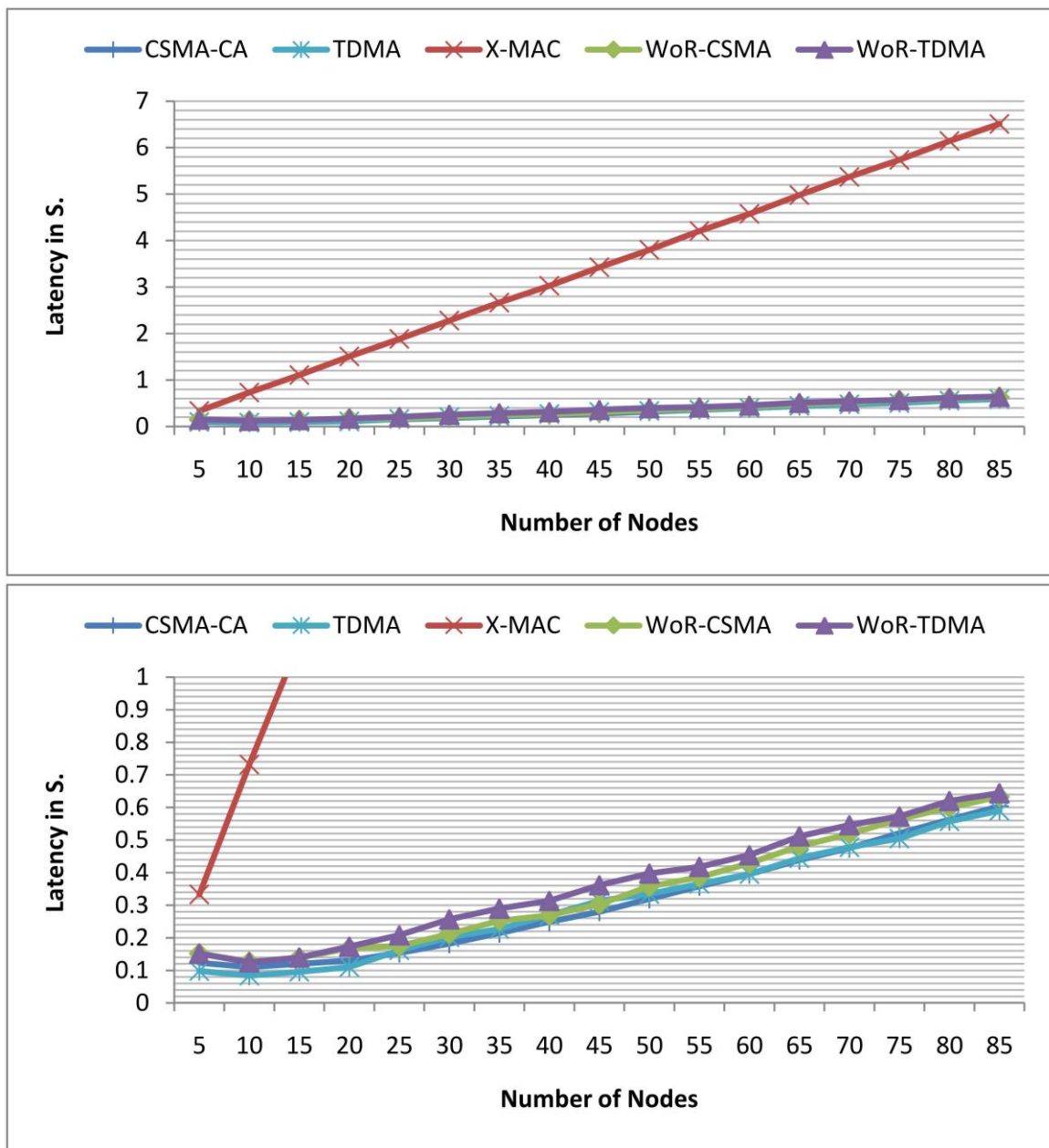


Figure 39: Average Latency with Respect to the Number of Nodes

Figure 39 shows the results of the simulation with respect to packet latency caused by the protocols examined. As indicated by the figure, TDMA and CSMA-CA consistently incurred the lowest latency. Similarly,

WoR-CSMA and WoR-TDMA also performed similarly respectively, maintaining a certain positive latency offset but maintaining the general slope characteristics of the standard protocols. X-MAC on the other hand, performed significantly worse than the other two protocols, with 700 milliseconds of latency for only 5 nodes in the cluster, up to over 6 seconds for large numbers of nodes. This value scaled linearly with respect to the number of nodes in the cluster.

3.2.2 Packet Loss

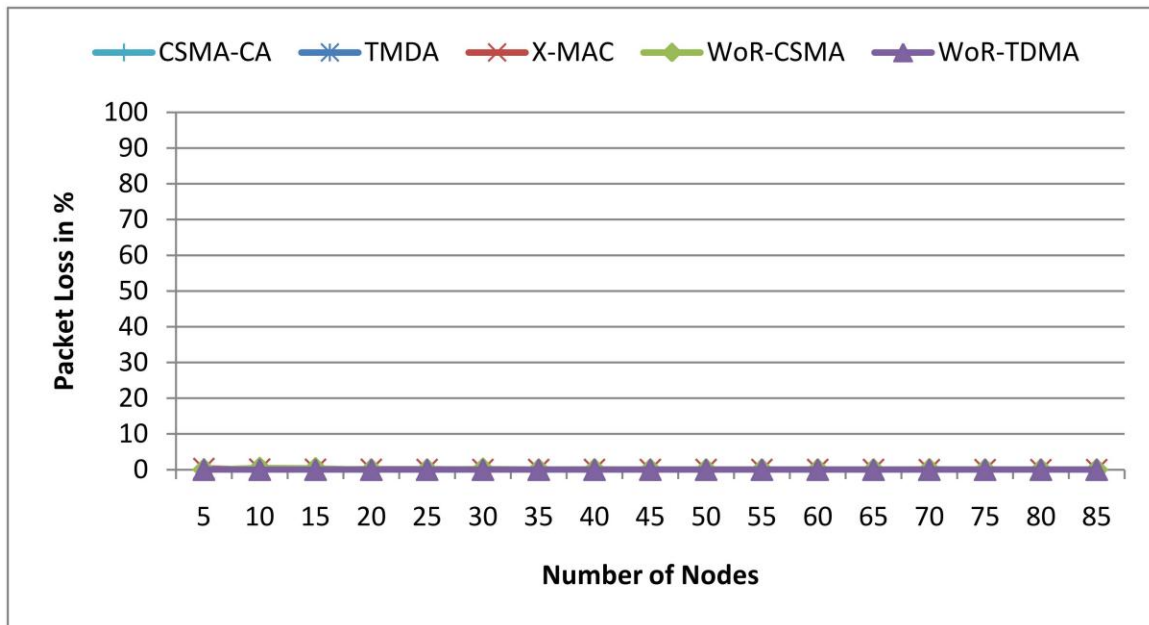


Figure 40: Packet Loss with Respect to the Number of Nodes

Figure 40 indicates that the values indicated for latency are valid for comparison as the effective packet loss, meaning packets which are not (eventually) delivered to the sink is close to zero for all protocols. These values oscillated between 0% and values less than 0.4% which can be attributed to timing and channel anomalies in the simulator.

3.2.3 Energy Consumption

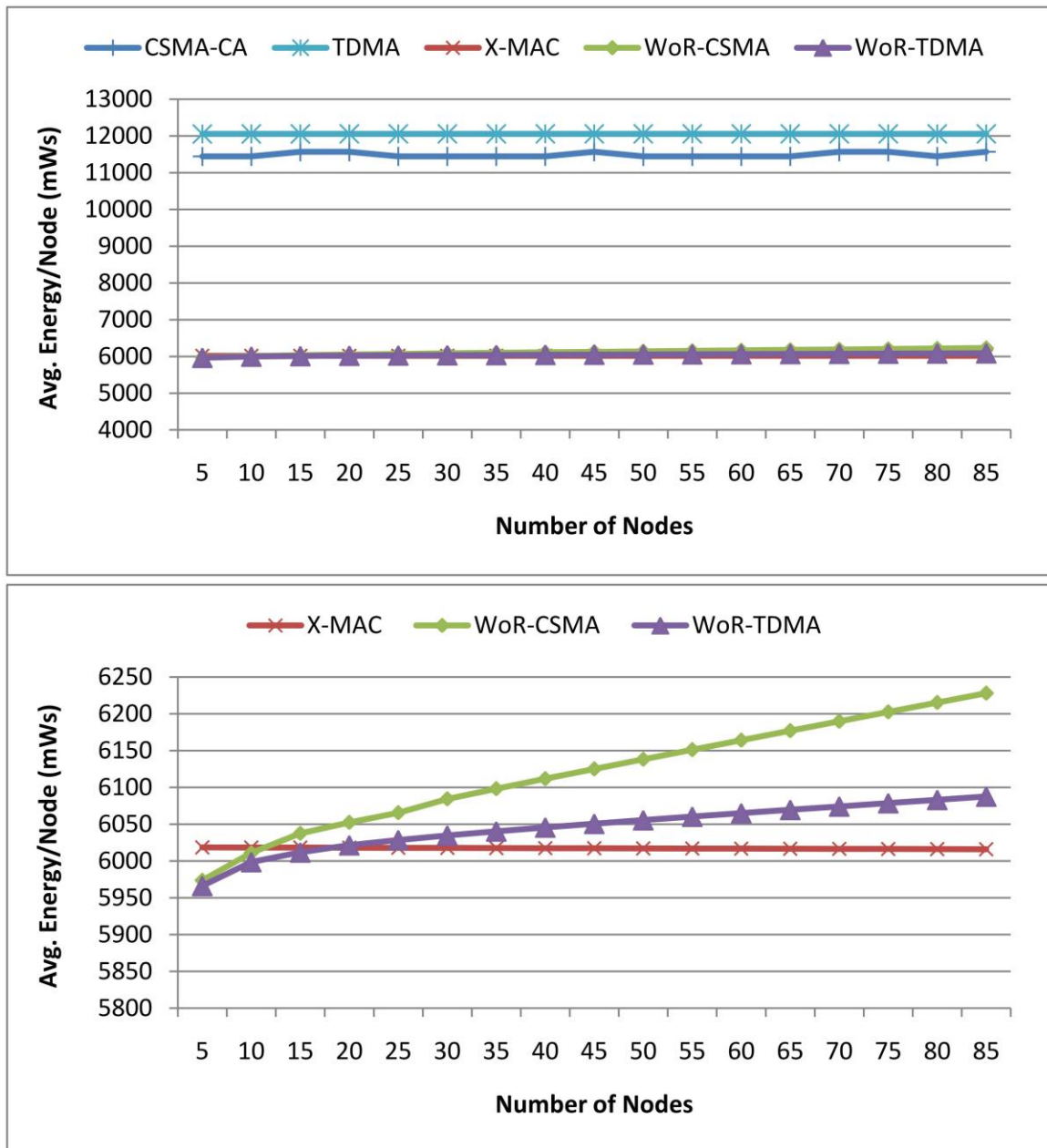


Figure 41: Average Energy Consumed with Respect to the Number of Nodes

When observing energy consumption for the scenario, CSMA-CA maintained a constant power consumption of approximately 11440 mW per node, regardless of how many nodes are in the cluster.



The cause of this is simple, since CSMA-CA is not capable of duty-cycling or receiving remote wake-ups, all nodes must remain in listen-mode on the channel for the BCA during the entire flight. As a result, since the costs for receiving and transmitting data are similar, the amount of energy consumed by a node is not dependent on how many other nodes are in the communication cluster. Similarly to CSMA-CA, nodes running TDMA must also remain in receive mode constantly as there is no mechanism to duty-cycle while waiting for the beacon. The consumption for TDMA is constant around 12056 mW per node, which is slightly higher than CSMA-CA due to the fact that the nodes remain in transmit throughout the duration of their slot period.

X-MAC on the other hand has a far lower energy consumption as each node is awakened asynchronously, transmits its data without contention, and then returns to sleep mode until after the next flight. This consumption behavior is also independent of the number of nodes in the cluster, as each node is able to sleep until it is up to communicate, after which it returns to sleep. Figure 41 compares the protocols in terms of energy consumption, and then adjusts the scale to detail the three duty-cycled protocols.

WoR-TDMA performs only slightly worse, with an average consumption per node of only 1.2% more than X-MAC for 85 nodes. WoR-CSMA is only slightly worse, climbing linearly to 3.4% greater than that of X-MAC for 85 nodes. It is also interesting to note that both WoR-CSMA and WoR-TDMA consume 0.8% and 0.9% less energy respectively for small amounts of nodes when compared to X-MAC, and WoR-TDMA consumes 0.1% less than X-MAC for 15 nodes. Unlike X-MAC, the consumption of WoR-CSMA and WoR-TDMA is dependent on the number of nodes in the network. This is due to contention during the communication period for one, and the energy required to collaboratively optimizing the contention period using the parameterized ACKs.

3.3 Application scenarios



3.3.1 Aeronautic application scenario

In order to confirm the applicability of the novel protocols for the aeronautic scenario, the DSID scenario was simulated.

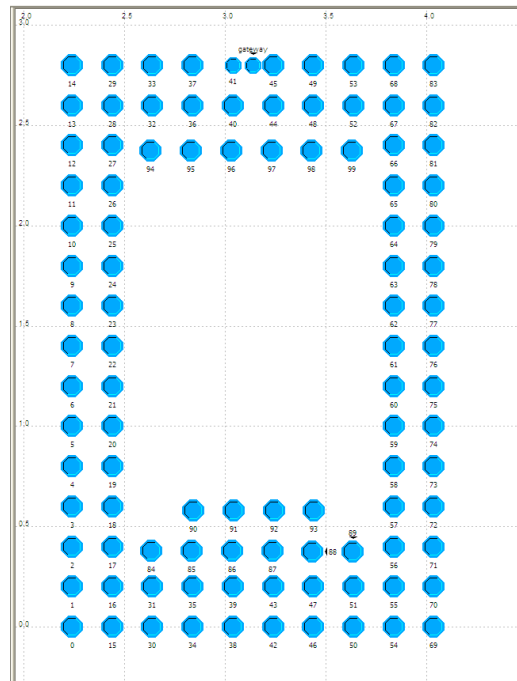


Figure 42: Topology for the Aeronautic DSID Scenario

The topology used for the evaluation is the Door Surrounding Impact Detection (DSID) scenario, which was selected because it is the most stringent in terms of its requirements. The topology used simulates many wireless acceleration sensors placed around an aircraft door as can be seen in Figure 42. For this scenario 2 hour flights were repeatedly simulated, where each node repeatedly generated a packet containing acceleration data every 10 minutes. After the two hours, a taxiing period of 10 minutes was simulated during which the nodes were woken and allowed to communicate. During this period, the latency, packet loss and power consumption of each node was monitored.

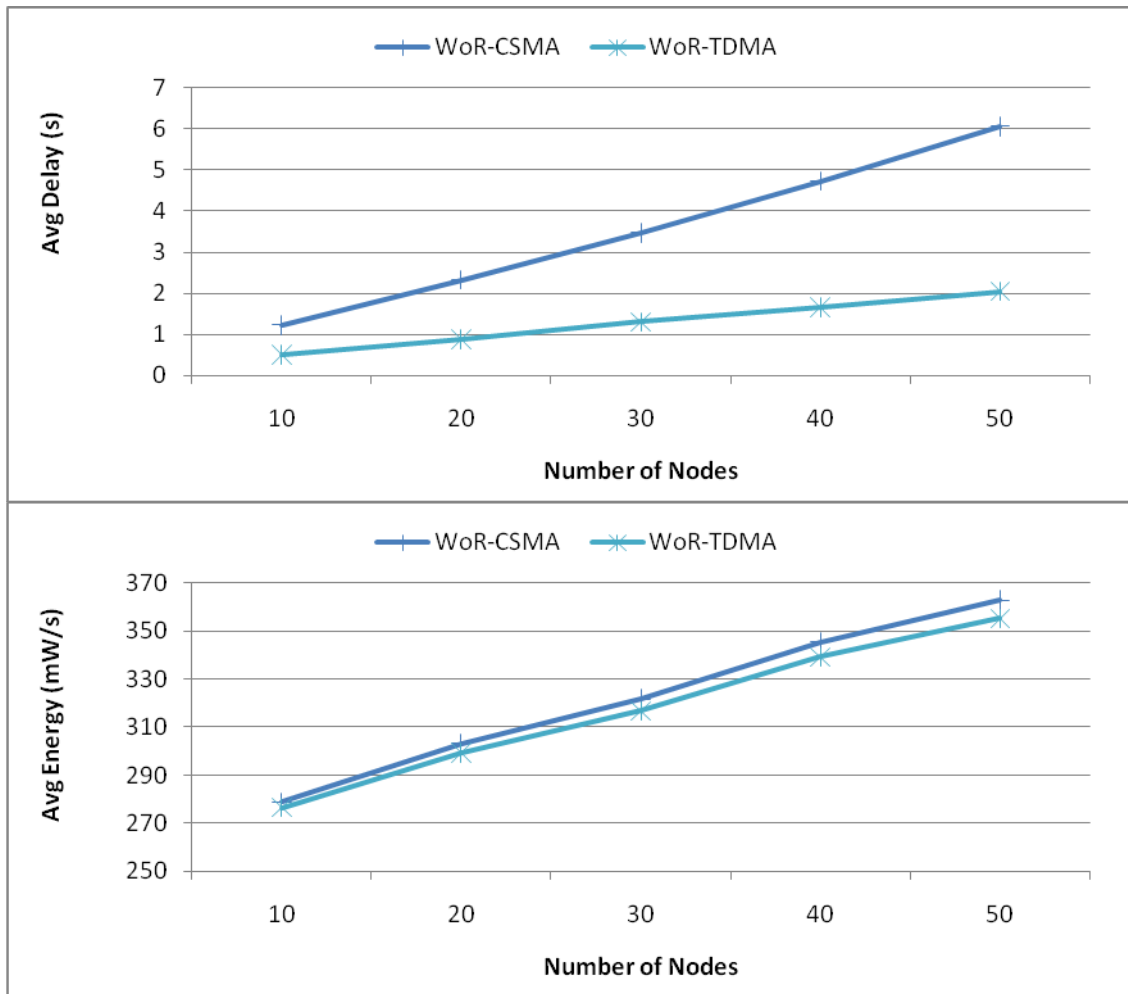


Figure 43: WoR-MAC/CSMA-CA and /TDMA Simulations for DSID

The results of the simulation can be seen in Figure 43. The first graph shows the average delay over all nodes and all flights for WoR-MAC with embedded CSMA-CA (WoR-CSMA) as compared to WoR-MAC with embedded TDMA (WoR-TDMA). The results indicate that WoR-TDMA achieves far better latencies which are much more scalable than WoR-CSMA. This is due to the fact that WoR-TDMA avoids the complications which come with clear channel assessment and avoids packet collisions all together.

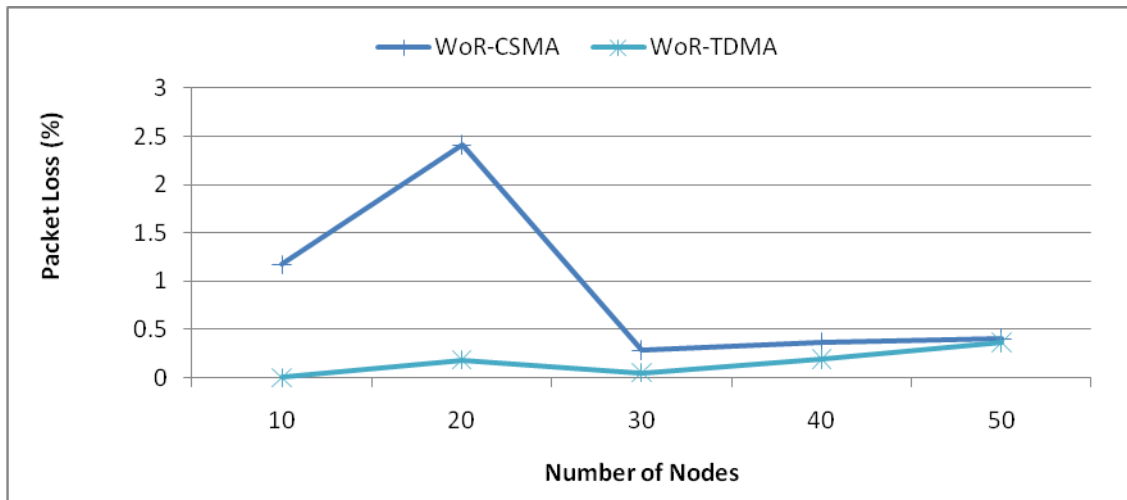


Figure 44: Packet Loss over the Number of Nodes

For these same reasons, the power graph in Figure 43 shows that TDMA incurs slightly lower power consumption than CSMA. Figure 44 indicates the number of packets lost by each of the protocols with respect to the number of nodes, once again showing that WoR-TDMA is advantageous. Since TDMA is a collision free protocol, loss is due to the dynamic channel as modeled in the simulator. For CSMA on the other hand, collision may occur when two nodes transmit synchronously, incurring retries and back-offs, and therefore greater latency and power consumption. Packet loss for CSMA then implies that the maximum number of back-offs has been reached, which is inefficient.



3.3.2 Automotive application scenario

Details about the automotive application scenario are available in the confidential version of D2.2.



4 CONCLUSIONS

The common simulation framework has been set-up and all contributing partners have a common understanding of the architecture and the components implementation. The distributed development and implementation of the single components is coordinated by means of a common SVN repository.

The channel models are obtained from the measurement campaigns and implemented in the simulation. The models of the network nodes are defined and implemented as well as their components. The components are modeled according to the hardware data sheets in order to provide realistic state transition timing and energy consumption. Models of the communication protocols have been implemented namely the newly developed MAC protocols WoR-MAC and BP-MAC, and the state-of-the-art protocols X-MAC and IEEE 802.15.4 MAC for comparison.

This enables us to assess the performance of the developed hardware components and communication protocols under realistic environment conditions, so that the risk for the application prototype development is minimized.

Performance evaluation and comparison as well as application scenario feasibility simulations were performed and show that the CHOSen node outperforms state-of-the-art sensor nodes in terms of power consumption in relation to achievable latency and throughput. The developed MAC protocols outperform standard MACs (802.15.4, X-MAC) in the relevant application scenarios. The application scenarios feasibility analysis showed that the CHOSen hard- and software is well fitted in terms of the defined requirements.

