



VUE²

Version 1.02

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1 Introduction

VUE² or (VUEE) which stands for Virtual Underlay Execution Engine, is an emulator for PicOS applications and their underlying networks. VUE² has been made possible by the fact that PicOS is a relatively straightforward descendant of a powerful simulator named SMURPH/SIDE. Thus, the emulation engine comprising VUE² is built around SMURPH with a relatively straightforward mapping of many PicOS operations to their SMURPH counterparts.

This document is a constantly evolving draft of VUE² description.¹ As the system is being developed, this description will change. Note that VUE² is modified not only in the course of its natural evolution (as all systems do), but also in response to new features being added to PicOS (which have to be mirrored in VUE²). At present, VUE² captures a prevailing subset of all PicOS features, including drivers for RF modules, pin/sensor interface, external memories, UARTs, and much more. Most importantly, it provides for an easy expression of network models and their virtual deployments. This means that PicOS praxes² can be run under VUE² on a multitude of virtual nodes behaving as if they were interconnected via realistic wireless links. Those virtual nodes can interface to real-life OSS agents in exactly the same manner that real nodes would. Thus, in addition to providing insights into the behavior of a PicOS praxis in the real world (performance assessment, network planning, power budgeting), VUE² also facilitates the development of various agents that have to be interfaced to that praxis to make the overall system complete.

Other important documents related to PicOS are listed at the end of this document (in Section 8: **References**).

2 Similarities and differences with respect to SMURPH

The striking similarity between PicOS and SMURPH is in the thread model. In both environments, a thread describes a finite state machine with the state transition function specified in terms of event wait operations. The rules for aggregating such operations and waking up the threads based on the occurrence of the awaited events are practically identical. In SMURPH, viewed as a simulator, the awaited events are delivered by abstract objects called *Activity Interpreters* [5], while in PicOS they are triggered by actual physical phenomena (e.g, packet reception, character arrival from the UART, and so on).

The first significant difference between the two systems is in the interpretation of time flow. In SMURPH, time is purely virtual, which means that formally nobody cares about the actual execution time of the simulation program, but only about the proper marking of the relevant events with virtual time tags. As in all event-driven simulators, the virtual time tags have nothing to do with real time. For example, a significant amount of calculations may be needed to advance the virtual time by a few microseconds, and no computation at all may be required to bypass several hours of idleness caused by no events in the system model. In the first case, the tiny advancement of the virtual time may take several hours of calculations, in the second case, the system may leap several hours into the future in no time at all.

Consequently, the formal useful semantics of SMURPH and PicOS threads are different. The actual execution time of a SMURPH thread is essentially irrelevant (unless it renders the model execution too long to wait for the results) and all that matters is the virtual delays separating the conceptual events. For example, two threads in SMURPH may be semantically equivalent, even though one of them may exhibit a drastically shorter execution time than the other (due to more careful programming and/or optimization). In PicOS,

¹ This partly explains why the document is not quite a masterpiece of literature: additions tend to be quick, ad-hoc, and local, as to reflect the spontaneous tweaks needed to make sure that VUE² stays in sync with our development work. I try to document everything, so the lag is minimal (typically zero). However, you shouldn't expect style, or even too much coherence across the different sections.

² PicOS term for "networked applications."



however, the threads are not (just) models but they run the actual thing. Consequently, the execution time of a thread may directly influence the perceived behavior of the PicOS node.

In this context, the following two assumptions have made our endeavor not only worthwhile, but also extremely successful:

1. PicOS programs are strongly reactive, i.e., they are practically never CPU bound. In other words, the primary reason why a PicOS thread is making no progress is that it is waiting for a peripheral event rather than the completion of a lengthy calculation.
2. If needed (from the viewpoint of model fidelity), an extensive period of CPU activities can be modeled in SMURPH by appropriately (and explicitly) delaying certain state transitions.³

Consequently, in most (or, practically, in all) cases, we can ignore the fact that the execution of a PicOS program takes time at all and only focus on reflecting the accurate behavior of the external events. With this approximation, the job of transforming a PicOS praxis into its VUE² model becomes reasonably simple. To further increase the practical value of such a model, SMURPH provides for the so-called *visualization mode* of its execution. In that mode, SMURPH tries to map the virtual time of modeled events to real time, such that the user has an illusion of talking to a real application. This is only possible if the network size and complexity allow the simulator to catch up with the model execution to real time. If not, a suitable slow motion factor can be employed. These issues are described in detail in the SMURPH manual [5].

While the syntax of PicOS threads is close to that of SMURPH processes, there are some differences. First of all, the language of SMURPH is C++, while PicOS is built around plain C. Second, a PicOS praxis is a one-node program, while the SMURPH model of that praxis must consist of multiple nodes running the same or possibly different programs. Additionally, the praxis code must be supplemented by the models of all those components of reality that are needed by the praxis to run. This brings about three issues:

1. Transforming the syntax of PicOS programs to that acceptable by SMURPH.
2. Putting multiple nodes, possibly with different programs, under the umbrella of a single SMURPH program (model).
3. Modeling the peripheral equipment needed by the praxis; also interfacing and parameterizing such models.

The third part is provided as a library of models whose interiors need not be interesting to the developer. This is to say, the third issue does not overly affect the operation of rendering a PicOS praxis executable under VUE², as long as the necessary peripherals have their models in the library. This is because the interface (API) to those models looks *exactly* as the PicOS API to the real equipment. For most of the open-ended parts of the interface, notably VNETI [4], the very same code (with some minuscule conditional fragments) is used in both cases. On the other hand, the first two issues come into play when the praxis is transformed/adapted for execution under VUE². Before version 0.9 of VUE², the adaptation was done manually. By following a set of mostly mechanical rules, the programmer would tweak the praxis source code and augment it with some extra files, such that the same code was accepted both by PicOS and by VUE². The previous version of this document included a detailed description of that procedure (which, in principle, is still applicable). At present, this task is accomplished by PiComp, the PicOS compiler, which comes with the PicOS package and is described in a separate document.

³ We were contemplating adding tools to VUE² that would make it possible to specify the timing of state execution in a PicOS thread. Such a specification could indicate that the amount of CPU time needed to run through a state is nontrivial and relevant. As of this time, there has been no practically inspired need for such a feature, and its prospective usefulness is at best unclear.



3 System outline

Figure 1 shows schematically the two possible ways of compiling a PicOS praxis. The right path corresponds to the “straightforward” case of turning the praxis into one or more (in the case of a multiprogram praxis) flash image files that can be uploaded into physical nodes. The left path outlines the transformation of the praxis into its VUE² model.

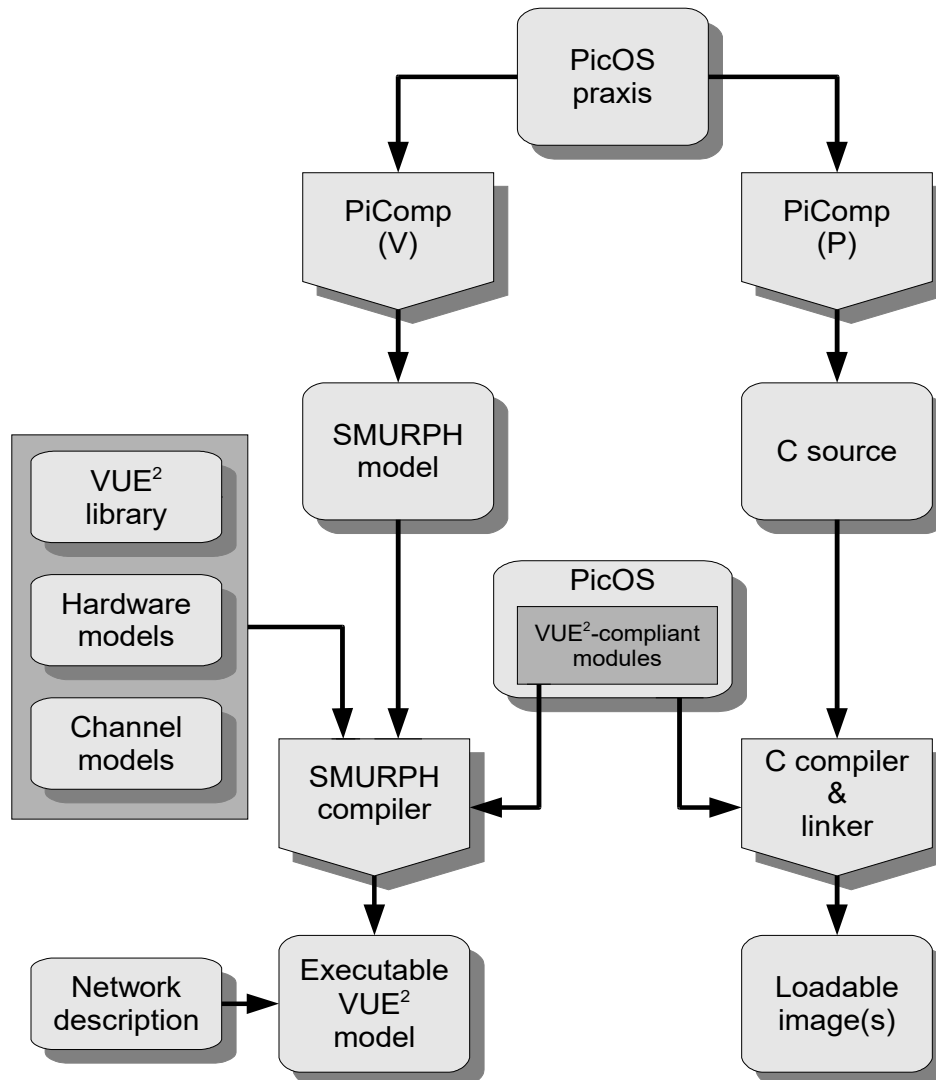


Figure 1: Compilation paths for a PicOS praxis.

The first stage of either path consists in preprocessing by PiComp [3]. The exact shape of that preprocessing is different in each case (PiComp is called with different parameters). For the right-hand-side path, the script merely converts PicOS-specific programming constructs to C, such that its output looks like a collection of programs in plain C that can subsequently be handled by the C compiler. For the VUE² path the task is more complex: in addition to translating the PicOS-specific programming constructs, PiComp turns the collection of (possibly multiple) programs comprising the PicOS praxis into a set of source files recognizable by SMURPH/SIDE. This is considerably more difficult. For one thing, it involves encapsulating the node program (or multiple such programs) into a collection of C++ methods that can be executed within the context of a virtual object representing a node,



such that multiple virtual nodes can coexist and meaningfully interact within the framework of the composite model. When subsequently processed by the SMURPH compiler, the output of PiComp is turned into a single executable constituting an emulation model for a complete system. That model encompasses a multitude of nodes, wireless channels, and whatever other physical components are needed to create a realistic replica of the target environment. Quantitative details of the model's instantiations are described in an input data file to the executable, so it is possible to run it for networks of different sizes, with different distributions of nodes, and so on. It is also possible to interface the virtual nodes to real-life OSS agents, such that those agents can be comfortably developed and tested in a convenient hassle-free setting.

Here is the list of components contributing to the complete PicOS platform:

1. The standard (vanilla) SMURPH/SIDE package constituting the emulation kernel of the system [5].
2. PicOS, which in addition to its current collection of VUE²-compatible praxes provides many files that are directly used by VUE² (the VUE²-compliant modules depicted in Figure 1). Also, PiComp [3] comes as part of the PicOS package.
3. VUE²-specific environment (SMURPH libraries and other files) that in combination with PicOS sources and praxes contribute to VUE² models.
4. PIP: the integrated, GUI-based, SDK for the platform providing a strong unifying glue [6]. While the platform can be used without PIP (with the assistance of command-line tools [7]), the SDK brings in friendly buttons and shortcuts for all the standard actions, including editing, compilation (both for VUE² and the real world), node flashing, virtual execution of VUE² models, debugging, and so on.

One special item included with the VUE² environment (point 3) is a program somewhat inappropriately named *udaemon* (Section 7). This is a Tcl/Tk (wish) script implementing an interface (GUI) to VUE² models.

The exact way of setting up the platform is described elsewhere [2]. Here we shall briefly comment on some VUE²-specific aspects.

3.1 Notes on configuring SMURPH/SIDE with VUE²

Suppose that the four packages have been unpacked at the same level (e.g., in the user's home directory). This is the recommended way of installing the platform, as outlined in [2]. They fill four separate source trees rooted at directories PIP, VUEE, PICOS, and SIDE.

In the present version of the platform, this step (I mean whatever is described by the remainder of this section as well as the next one) is performed automatically by the deploy script [2]. It can be done manually, e.g., in a custom setup. The procedure is basically identical to setting up SMURPH/SIDE for a stand-alone operation (as described in [5]), except for declaring:

1. the VUE² library to be searched automatically by the SMURPH compiler for #included files
2. the (optional) data include library to be searched automatically for components included from the XML data set to the simulator

Thus, the relevant fragment of your conversation with maker (the SMURPH installer) when installing the package should resemble this:

```
Now, please enter the list of paths to 'include' libraries
(which can be absolute or relative to your home directory), each
path in a separate line. Enter an empty line when done. This
path:
```

```
/home/pawel/SIDE/Examples/IncLib
```



is standard and need not be specified. If you want to exclude the standard path, enter '-' as the only character of an input line.

VUEE/PICOS

Now, please enter the list of paths to data 'include' libraries, i.e., the directories that will be searched for <include>s in XML data. Each path must be specified in a separate line, with an empty line ending the sequence. There is no default.

PICOS/Apps/DataLib

where the lines in italics are your responses (assuming that VUE² has been unpacked in the home directory). You can specify the complete paths of the directories (beginning with /) if in doubt. Note that the default for the source include path suggested by maker is retained, and one more (VUE²-specific) include path is added. The standard (default library) is also needed as it provides the models of wireless channels used by VUE².

Defaults can be selected for the remaining installation parameters. The monitor, needed for the Java DSD applet is optional (and rather useless for VUE²). You probably shouldn't bother with it at all: the monitor connection of SMURPH is not required for interfacing VUE² models to external agents, and its only practical advantage is for intricate monitoring of models for SMURPH debugging.

You have to assign a non-default name to the mks program generated by maker, i.e., to the actual compiler of VUE² models. That name must be one of vuee, vue, vue2. This is required for two reasons. First, PiComp will search for the SMURPH compiler under one of these three names. Second, when called under one of these names, the SMURPH compiler will recognize that it is running for VUE² and will automatically select the right set of parameters (which otherwise would have to be specified explicitly). In particular, the compiler automatically forces -L and -W, i.e., disables the (redundant) models of wired channels and selects the visualization mode of SMURPH. Note that all VUE² models require -W to compile (while -L is optional).⁴

It is possible to have a single installation of SMURPH/SIDE to be used for VUE² as well as for other purposes, i.e., simulation of network protocols (which has been the traditional role of SMURPH). Having run maker once to create the vuee compiler, you can run it again possibly selecting another configuration of include libraries and assigning the standard (or different) name to the mks compiler. Depending on which compiler version is invoked, the corresponding include *libraries* will be referenced and the respective set of options will be applied. Note that the alternative version of the SMURPH compiler can also be created manually following the automatic setup by the deploy script [2].

3.2 Notes on setting up VUE²

The VUE²-specific components unpack into directory VUEE. It is convenient if this directory occurs at the same level as the PICOS directory. The procedure of setting up this component is simple and consists in providing links from VUEE/PICOS to some files in the PICOS tree. Those files correspond to those elements of PicOS that have been made VUE²-compliant, i.e., can be used directly by SMURPH as fragments of the VUE² model. In particular, tcv.c (implementing VNETI [4]) is one of those files.

Again, the deploy script [2] takes care of this end as well, so normally there is no need to worry about the details. If, for some reason, you want to perform this step by hand (rather than let deploy do its job), you should move to VUEE/PICOS and execute ./mklinks in that directory. This will only work if that directory occurs at the same level as VUEE. If this is unsuitable for whatever reason, you can edit the mklinks script specifying the correct path to PICOS.

⁴ Thus, wireless and wired channel models can coexist, if needed (the system is capable of modeling hybrid networks).



Formally, the proper order of unpacking and installing the three systems (in case you insist on doing it manually) is: PICOS, VUEE, SIDE, PIP. This is because VUEE needs links to PICOS and SIDE needs VUEE/PICOS as an include library.

3.3 Legacy praxes

The old way of maintaining VUE²-compliance of praxes, before PiComp, involved elaborate sets of macros, headers, and rules that must have been obeyed by the programmer to make sure that the same set of source files could be compiled for a target device (basically by the C compiler) as well as into a SMURPH model. There still exist praxes built according to those rules. To compile them, you just move into the praxis directory and execute vuee (or whatever name you have assigned to the VUE²-SMURPH compiler – see Section 3.1). The outcome of this compilation is an executable file named side (side.exe under Cygwin). By running this file (with a suitable data file), you will execute the model. To compile the same praxis for a target board, you execute (in the same directory):

```
mkmk boardname
make
```

Note that the PicOS compiler (mkmk) is able to accommodate so-called multiprogram praxes, i.e., multiple programs (translating into different flash Image files) in the same directory (refer to [7], Section 5 for details). This feature may not seem very useful when viewed solely from PicOS's angle. In the context of VUE², this is needed in situations when a single VUE² model must accommodate multiple programs (i.e., multiple types of nodes). Such programs are usually strongly related, so it makes sense to keep them in the same directory.

It is recommended that any legacy praxis that has to undergo non-trivial enhancements, extensions, or modifications be first converted to the new format (see [1] and [3]). The details of the old format in the context of maintaining VUE²-compliance of praxes can be found in older versions of this document (retrievable from the GIT repository of VUEE). Refer to [3] for a discussion of the VUE²-compliance issues for praxes adhering to the new format.

3.4 Praxis options

File options.sys [7] is used by PicOS to select the optional components of the system for real-life compilation. For a multiprogram praxis, there are multiple options files named options_XXX.sys, where XXX is the program label, i.e., a piece of string identifying the program (see [7], Section 5). The role of the praxis options files has been controversial and questionable. Those files were originally introduced as the sole way to parameterize the praxis program(s) for different hardware. With the introduction of comprehensive board definitions stored in dedicated directories (R061030A), most of the hardware-related parameterization was transferred to the subdirectories of BOARDS, with the role of options.sys/options_XXX.sys taken over by board_options.sys (a standard board description file). Still, the praxis options files have been used (more than occasionally) for various “corrections” and “adjustments”, which probably has been bad methodology. Formally, mkmk [7] considers praxis options files optional: they don't have to be present in the praxis directory, if the program(s) can live with the “official” set of options that come from the board(s).

Before version PG121113A, VUE² was agnostic to BOARDS, i.e., it didn't see the real-life hardware configuration of the praxis beyond the definitions it could find in the local options files. Thus, even though mkmk needed no local options files for real-life compilation, VUE² still needed them in order to know how to configure those elements of the model that had to be compiled differently depending on the options of virtual hardware. One important “hardware” option of PicOS needed by VUE² is the radio module selection. It is not needed as much by VUE² as by the networking components of PicOS (net.c) that (alongside VNETI, i.e., tcv.c) compile with VUE² in their original (PicOS) versions.

Since PG121113A, the local options files are optional also for VUE². This is accomplished by letting VUE² see the true hardware configuration of the praxis from where it can infer the



configuration of the hardware model. The most natural way to do it right is via PIP which maintains the complete configuration of the project (both for real and virtual lives). Technically, in an emergency, it can also be done manually by telling PiComp the locations of the requisite board directories (see [3]).

If the set of boards for the praxis is known to PIP (i.e., the praxis has been also configured for real-life compilation), PIP will instruct PiComp (using the -H call argument, see [3]) to implicitly include at the front of every separately compiled program file the file `board_options.sys` from the directory of the respective board (the one associated with the program for PicOS compilation). In that case, PiComp will also define these constants, separately for each program of the praxis:

```
#define BOARD_XXXXX
#define BOARD_TYPE XXXXX
```

where `XXXXX` stands for the board name, i.e., the name of the board's directory. The same constants are defined by `mkmk` for real-life compilation (see Section 3.2 in [7]).

Regardless of whether the praxis is configured for real-life compilation or not, PiComp will try to include at the beginning of every independently compiled program file the respective local options file from the praxis directory, but it will not object if that file is absent (a rudimentary warning is left just in case). For a multiprogram praxis, it will first try to look up a file named `options_xxx.sys`, where `xxx` is the program label (see Section 5 in [7]). If no such file is available, but the generic `options.sys` file is present, PiComp will include that file instead. The local options file formally follows the board options file (if one is included as well), so local definitions can override board definitions. This agrees with the way `mkmk` interprets those files for real-life compilation. Note that only `options.sys` is looked up in the case of a single-program praxis.

The potentially confusing way of splitting the responsibilities between PiComp and PIP results from the fact that only PIP maintains a consistent view of the assignment of boards to the programs of a praxis, which assignment comes naturally as an element of the project description. PiComp by itself doesn't care about PIP projects.

Note that legacy praxes, i.e., ones that cannot be handled by PiComp, must use local options files to define the options of their virtual hardware. This is because the "implicit inclusion" of a computed header file can only be done after some creative parsing.

If you have to make some of the code conditional on whether it is compiled for real life or for a VUE² model, you can rely on the symbolic constant `__SMURPH__` (double underscores on each side) which is only defined if the program is being compiled for VUE². Needless to say, you should minimize this kind of dependence of your praxis. It is sometimes needed if the real-life incarnation of the praxis references some exotic hardware whose VUE² model is non-existent or approximate.⁵

4 Input data

The input data file parameterizing a VUE² model follows an XML format. Below is a complete sample data file describing a three-node network:

```
<network nodes="3" radio="3" port="2234">
  <grid>0.1m</grid>
  <channel bn="-110.0dBm">
    <propagation type="shadowing" sigma="1.0dB">
      RP(d) = received power at distance d
      XP      = transmitted power
      X       = lognormal random Gaussian component
    =====
      RP(d)/XP [dB] = -10 x 3.0 x log(d/1.0m) + X(sigma) - 38.0
```

⁵ For example, there may be a sensor (otherwise accessible via the standard interface) requiring some special initialization (for which no VUE² model is present). In such a case, the initialization code can be encapsulated into `#ifndef __SMURPH__`.



```

=====
</propagation>
<cutoff>-120.0dBm</cutoff>
<ber>
    Interpolated ber table:
    =====
        SIR          BER
        50.0dB       1.0E-6
        40.0dB       2.0E-6
        30.0dB       5.0E-6
        20.0dB       1.0E-5
        10.0dB       1.0E-4
        5.0dB        1.0E-3
        2.0dB        1.0E-1
        0.0dB        2.0E-1
        -2.0dB       5.0E-1
        -5.0dB       9.9E-1
</ber>
<frame>
    min preamble (aka synchbits) = 8
    physical bits per byte       = 12
    extra framing bits           = 0
</frame>
<rates boost="yes">
    0      9600      6.0dB
    1      38400     0.0dB
    2      200000    -10.0dB
</rates>
<power>
    0      -30.0dBm
    1      -15.0dBm
    2      -10.0dBm
    3      -5.0dBm
    4       0.0dBm
    5       5.0dBm
    6       7.0dBm
    7      10.0dBm
</power>
<channels number="255">
    separation
    20dB 29dB 38dB 46dB 54dB 62dB 70dB 78dB 86dB 94dB 102dB
</channels>
<rsi>
    0      -202.0
    255    53.0
</rsi>
</channel>
<nodes>
    <defaults>
        <memory>1124 bytes</memory>
        <processes>16</processes>
        <radio>
            <power>7</power>
            <rate>1</rate>
            <boost>1.0dB</boost>
            <channel>4</channel>
            <preamble>32 bits</preamble>
            <lbt>
                delay      1msec
                thresholds  -109.0dBm
                           -99.0dBm
                           -89.0dBm
                           -80.0dBm
            </lbt>
        </radio>
    </defaults>
</nodes>

```



```

                                -70.0dBm
                                -45.0dBm
                                -30.0dBm
                                0.0dBm
                                tries      8
        </lbt>
        <backoff>
            min      4 msec
            span     63 msec
        </backoff>
    </radio>
    <uart rate="9600" bsize="12" mode="direct">
        <input source="socket"></input>
        <output target="socket" type="held"></output>
    </uart>
    <eeprom size="524288" clean="00">
        <chunk address="0">00 01 02 04 08</chunk>
        <chunk address="8192" file="eblock.bin"></chunk>
    </eeprom>
</defaults>
<node index="0" hid="0xBACA0020">
    <location movable="no">1.0 4.0</location>
    <preinit tag="ESN" type="lword">0x8000ff01</preinit>
</node>
<node index="1" start="off" hid="0xBACA0021">
    <location>1.0 10.0</location>
    <emul>
        <output target="socket" type="held"></output>
    </emul>
</node>
<node hid="0xBACA0200">
    <eeprom size="10485760,20480" image="node2_eeprom.img"
        clean="00" erase="page" overwrite="no"
        timing="0.000004,0.000006,
            0.000004,0.000034,
            0.000030,0.000038,
            0.000005,0.040000">
    </eeprom>
    <iflash size="512,2" clean="ff"></iflash>
    <sensors>
        <input source="socket"></input>
        <sensor vsize="2" delay="0.05">4095</sensor>
        <sensor vsize="2" delay="0.1,0.5" init="3">999</sensor>
        <actuator vsize="4" delay="0.01" init="0"></actuator>
    </sensors>
    <location>1.0 10.0</location>
    <ptracker>
        <output target="socket"/>
        <module id="cpu">0.3 0.0077</module>
        <module id="radio">0.0004 16.0 30.7 30.7</module>
        <module id="storage">
            0.030 0.030 10.0 15.0 17.0 16.0
        </module>
        <module id="sensors">0.0 2.5</module>
    </ptracker>
</node>
</nodes>
<roamer>
    <input source="string">
        R 2 [1.0 1.0 21.0 24.0] [0.5 1.8] [1.0 6.0] -1
    </input>
</roamer>
<panel>

```



```

        <input source="string">T 10.0\nO 1\nT +5.0\nF 1</input>
    </panel>
</network>

```

Figure 2: A sample data set for a VUE² model.

Every data file describes a single <network>. The first attribute of the <network> element (nodes) is mandatory and specifies the total number of nodes (of all types). The second attribute (radio), if present, tells the number of nodes that will be interfaced to the RF channel. If this attribute is missing, it defaults to the total number of nodes, unless the data set contains no specification of a radio channel, in which case it defaults to zero. These numbers remain fixed during the execution, but the nodes may exhibit a dynamic behavior, i.e., they can turn themselves on and off and move around.

One more (optional) attribute of <network> is port, which can be used to assign a non-standard port number to the socket opened by the program for connections from agents (see Section 6).

Many input elements include numbers. Typically, besides numbers, such an element may contain non-numeric text, which is ignored (treated as a comment). For example, the only relevant items from the <propagation> element in <channel> are the numbers -10, 3.0, 1.0, 38.0. Also, any non-numerical characters in the otherwise numerical attributes of elements (like the letters dBm in "-110.0dBm") are ignored. Thus, the equivalent comment-free specification of <propagation> from Figure 2 is:

```

    <propagation type="shadowing" sigma="1.0">
        -10 3.0 1.0 38.0
    </propagation>

```

Note that the minus sign apparently preceding 38.0 has been ignored: this is because of the space separating it from the first digit (be careful).

The good news is that the model quite meticulously echoes the input data set to its output, so one can easily double check whether the data make sense. The echoing only happens after the error checking and interpretation, so it concerns the input data as recognized and accepted by the program.

4.1 Superfluous elements

Generally, when interpreting a data set, VUE² ignores any elements (and element attributes) that it doesn't recognize.⁶ This also applies to multiple occurrences of the same element (i.e., the same element name). For example, the simulator expects just one occurrence of <propagation> within <channel>, so only the *first* occurrence will matter and any subsequent occurrences of this element will be ignored. This may be useful for temporary modifications of data sets (leaving previous definitions as comments without actually commenting them out). Note, however, that some elements occur naturally multiple times (e.g., <node>). In such a case, all elements with the given name are looked up and interpreted (in the order of their occurrence in the data file)

4.2 Grid

The optional <grid> element has no arguments, and its text must include a single (floating point) number. This number specifies the granularity (in meters) of the coordinate grid for node deployment and movement. By default, the value of grid is 1.0, which means that node locations will be rounded (rather crudely) to full meters. This parameter directly determines the internal discrete granularity of virtual time in SMURPH (the so-called ITU [5]), which is equal to the amount of time required for a radio signal (propagating at 299,792,458 m/s) to cross the grid unit.

⁶ The data set may also contain some elements and attributes unrecognizable by the simulator, but interpreted by udaemon as visualization hints (Section 7.11).



4.3 Channel

This element describes a radio channel. It is optional, which means that you can also model in VUE² nodes that are not equipped with radio interface. If no radio channel is present in the data set, then no nodes are interfaced to the radio, which also means that a radio attribute of <network> specifying a nonzero number of nodes is illegal.

The present version of VUE² offers three built-in channel models, or rather three variants of the propagation component for a generic model of radio channels. More such variants may be added in the future. The set of parameters describing a radio channel is partitioned into two parts: those (in principle) applicable to all channels, and those specific to a particular propagation model. The latter subset of parameters is covered by the <propagation> element.

4.3.1 The generic part

The model deals with signals which are virtually generated, propagated, and combined.⁷ The primary representation of a signal is its *level* amounting to a floating point number. A signal is transmitted at some (transmission) level, then, as the signal propagates, its perceived level at any point is modified (typically attenuated) according to the propagation model. At a recipient, all the levels of all perceptible signals, plus the background noise, are added and assessed for interference. The ratio of the level of one selected signal to the combined (added) levels of all the other signals (including the omnipresent background noise) is called the signal-to-noise ratio (SNR) and determines the bit error rate (BER). That in turn affects the reception opportunities for the packet carried by the signal. A detailed description of the SMURPH tools available to VUE² for modeling the channel behavior can be found in [5].

No explicit units are assigned to signal levels by the model, because all that matters in the interpretation of a signal level is its ratio to other signal levels. Thus, by properly scaling those ratios we implicitly assign an interpretation. Needless to say, when modeling specific devices, a standard unit, like dBm makes perfect sense (and this is our unit of choice for the subsequent discussion). Signals and their ratios (e.g., attenuation, SNR) are expressed logarithmically (in dB) in the data set; the simulator transforms them to the mostly invisible, linear scale for internal use.

The (exchangeable) <propagation> section of a channel description will be discussed separately (see Sections 4.3.2 and 4.3.3). Its purpose is to provide a procedure for calculating how the level of a signal transmitted at some point *A* should appear when viewed at another point *B*. Once we assume that that procedure has been settled, the rest of the channel parameters can be discussed without referencing the propagation part.

The *bn* attribute of the <channel> element (page 10) specifies the constant level of background noise.⁸ Note that the suffix dBm following the number is merely a comment. If not specified, the attribute defaults to zero (no background noise). You cannot explicitly specify a zero *bn*; for example, *bn="0"* will translate into 0dB (relative to the signal level unit), i.e., the linear value of 1 unit, which (assuming 1dBm as the unit) is huge. If you want to specify something effectively amounting to zero, use a very large negative number.

The <cutoff> element defines a single floating point number interpreted as the so-called cut-off signal level. This is a threshold for the received signal level below which it can be safely assumed that there is no signal at all.⁹ This value is used to calculate the cut-off distance restricting the simulator's internal population of neighborhoods in the model, which may impact the model's execution speed, especially for large networks. A higher cut-off level translates into a smaller cut-off distance and reduced size of a typical neighborhood, which

⁷ Note that the neutrino channel model (Section 4.3.4) is an exception in that the signal levels, attenuation, interference don't matter: all transmitted packets are always received as long as some simple (discrete) criteria are met. Needless to say, that model is not meant to reflect any realistic RF propagation environment, so let us ignore it in this discussion.

⁸ The attribute is ignored by the neutrino propagation model (Section 4.3.4).

⁹ The element is ignored by the neutrino propagation model.



also reduces the processing time (less effort is required to combine and assess the signals). If the element is absent, the cut-off value defaults to zero (with the same provision as for the *bn* attribute). Note that the cut-off of zero means that no signal is too small, i.e., the simulator perceives the entire network as a single global neighborhood (every node can be potentially heard by any other node).

All signals arriving from multiple transmitters within the cut-off range (distance) of a receiving node N_r combine additively.¹⁰ The SIR of a single signal perceived by N_r is equal to the value of that signal level at N_r (accounting for its attenuation prescribed by the propagation part of the model) divided by the sum of all the other signals arriving at N_r , augmented by the background noise (the *bn* attribute of <channel>). Then, the table from the <ber> element is consulted to determine the probability of a bit error. That table is an array of numbers occurring in pairs. The numbers in the first column must be decreasing, while those in the second column must be non-decreasing (normally they are increasing). This is a discrete specification of a function that translates the signal to interference ratio (SIR) at the receiver into a bit error rate (BER), i.e., the probability that a single bit is received in error. The complete BER function for all possible values of SIR is obtained by interpolating the table. If the SIR is greater than or equal to the first value in the table, then the bit error rate is determined by the first entry (for example, it never decreases below 10^{-6} in the channel described in Figure 2). If it is less than the last value, then the bit error rate is 1, i.e., no reception is possible.

The bit error rate applies to the so-called “physical bits,” which are also used in determining the effective transmission rate. The three numbers within the <frame> element stand for the minimum preamble length, the number of *bits* per byte, and the number of any extra *bits* needed to frame a complete packet. The first number (known as *syncbits*) gives the minimum number of successfully received preamble bits before an incoming packet can qualify for a reception attempt.¹¹ The second value describes the way to translate physical bits into logical bits specifying the number of physical bits in one logical byte (octet). This translation accounts for the encoding, e.g., 6-bit symbols encoding 4-bit nibbles. The third parameter (also expressed in physical bits) covers any special (non-preamble) components of the frame that are invisible to the receiver software but contribute to the overall length of a transmitted and received packet (the start symbol/word is a good example). The <frame> element is allowed to specify two numbers instead of three: in such a case, they are interpreted as the number of physical bits in a byte and the number of extra framing bits (with *syncbits* assumed to be zero).

Refer to the SMURPH manual [5] for a discussion of the dynamics of the interference model. The assessment method responsible for detecting the beginning of a packet at a receiver (RFC_bot) checks if at least *syncbits* (physical) bits of the preamble immediately preceding the first bit of the actual packet have been received without an error, according to the bit error rate calculated as explained above. The second assessment method (RFC_eot), determining the final success of a packet reception, is not used in the channel model. Instead, the receiver invokes RFC_erd to await the first bit-error event in the packet. The reasonable simplification assumed in the model is that the first error bit will render the packet invalid. For most symbol-based encoding schemes, a single bit error renders the current symbol invalid, so the receiver may immediately decide that the packet is erroneous. For straightforward encoding schemes, the bit error will cause a checksum (CRC code) mismatch (essentially to the same effect).

The <channel> element appears to describe a bit more than just the radio channel: some of its parameters seem more related to the characteristics of the RF modules wired to the nodes. This concerns the elements <power>, <rates>, <channels>, and <rssi> (described

¹⁰ This (and the entire discussion of SIR and BER) does not apply to the neutrino model. There are no bit errors in that model.

¹¹ This attribute is ignored by the neutrino propagation model.



below in detail). Although, it might make sense to attach those attributes to individual transceivers (possibly facilitating their potential diversity),¹² the present description associates them with the channel model where they are defined globally for all RF modules in the network. Owing to the fact that all RF drivers in PicOS share practically the same logical structure, it makes sense to encapsulate their hardware-specific properties into parameters that can be set in the input data file. This way, functions like `phys_cc1100`, `phys_dm2200` point to essentially the same driver model, while the proper setting of the channel parameters in the input data should bring that model close to the target hardware.

The `<power>` element maps the power settings of the RF module into actual power levels (in the assumed units of signal level, i.e., dBm).¹³ The first column of numbers (see page 11) lists the small integer values usable by the praxis as arguments of `PHYSOPT_SETPOWER`, with the corresponding settings of the actual transmission power (in dBm) appearing in the second column.

In a similar way, `<rates>` declares the selection of bit rates available to `PHYSOPT_SETRATE`. If the boost attribute of the `<rates>` element is yes (as in Figure 2), then there is a third column of numbers to specify rate-specific factors (boosts) applied to the signal at reception. Specifically, that boost (which can be negative) is only applied for the calculation of the bit error rate (it does not affect the perceived signal level at the receiver). For example, the setting in Figure 2 (page 11) implies that a packet transmitted at 38400 bps receives no boost (its BER is determined by consulting the `<ber>` table at the received signal level of the packet divided by the combined interference), while a packet transmitted at 9600 bps gets a 6dB boost over the interference before the `<ber>` table is looked up, which means that its BER is going to be lower. This way, different rates may result in different effective transmission ranges. If the boost attribute is absent (or different from yes), the specification consists of two columns and there are no rate specific boost factors (equivalent to 0dB boost for all rates).

If a `<channels>` element is present, it describes the number of channels settable by the praxis with `PHYSOPT_SETCHANNEL`. The optional sequence of FP numbers appearing within the text of that element refers to channel separation in dB. Normally, these numbers are increasing: the first number gives the separation between two adjacent channels, the second between channels n and $n+2$, and so on. The separation becomes infinite when the numbers run out. In particular, if no numbers are specified at all, the separation between any pair of different channels is infinite.

Channel separation data is used when signals transmitted on different channels are assessed for their contribution to interference with some packet. The levels of such signals are then divided by the separation of their channels from the channel on which the packet is being received. If the separation is perfect (infinite), signals sent on different channels are completely ignored in such cases.

The `<rates>` element is always mandatory (regardless of the channel type). The `<power>` element is required for all propagation models except *neutrino* (Section 4.3.4) where it is ignored. In a simple case, e.g., if there is only one available power setting, the `<power>` element may contain a single FP number: the power setting with the implied index of zero. On the other hand, `<channels>` is always optional. If absent, there is only one channel shared by all nodes and its number is zero.

The `<rssi>` element describes the way of transforming the received signal strength into RSSI indications (and vice versa).¹⁴ For the shadowing channel model, its sole purpose is to insert meaningful RSSI values into the trailers of received packets. The element is then optional: if absent, no RSSI indications are returned to the praxis (the corresponding packet byte is

¹² Some diversity of this sort might be occasionally useful, e.g., the power settings and RSS indications of CC1100 and CC1101 (also CC430) are slightly different, although the differences are generally small and insignificant.

¹³ The element is ignored by the neutrino propagation model.

¹⁴ The element is ignored by the neutrino propagation model.



always zero). For the sampled channel model, the table is mandatory, because the samples deal with RSSI (so the model must know how to translate RSSI into signal levels).

The first column of numbers in the <rss> element refers to the indications returned to the praxis, while the numbers in the second column describe the corresponding received signal levels. Values in between are interpolated.

4.3.2 The shadowing propagation model

This model is selected by setting the *type* attribute of the <propagation> element to *shadowing*. One more (optional) attribute of <propagation> is *sigma* providing the mean value of the normally distributed randomized component of the attenuation value (in dB). If the attribute is absent, *sigma* is set to zero, which means that the attenuation is never randomized.

Signal attenuation is described by this formula:

$$\left[\frac{P_r(d)}{P_r(d_0)} \right]_{dB} = -10\beta \log\left(\frac{d}{d_0}\right) + X(\sigma_{dB})$$

where $P_r(x)$ is the received signal level at distance x , d_0 is an (intentionally small) reference distance, β is the loss exponent, and X is a Gaussian random variable with zero mean and standard deviation of σ_{dB} (attribute *sigma*). For our purpose, we transform the formula to give us signal attenuation at distance d , which we can directly plug into the respective assessment method in SMURPH [5]:

$$\left[\frac{P_r(d)}{P_x} \right]_{dB} = -10\beta \log\left(\frac{d}{d_0}\right) + X(\sigma_{dB}) - L(d_0)$$

where P_x is the transmission power and $L(d_0)$ is the calibrated loss at the reference distance d_0 . This formula is only meaningful when $d > d_0$. It is tacitly assumed that transmission at a shorter distance incurs the same attenuation as a transmission at the reference distance d_0 . This is exactly the formula from the <shadowing> element on page 10 (Figure 2), i.e.,

$$RP(d)/XP [dB] = -10 \times 3.0 \times \log(d/1.0m) + X(\sigma) - 38.0$$

with the parameter values: $\beta=3.0$, $d_0=1.0m$, $\sigma_{dB}=1.0$ (note that *sigma* is an attribute of <propagation>) and $L(1m)=38dB$.

Note that the value produced by the attenuation formula (generally, by the attenuation algorithm of a given propagation model) is applied as a multiplier to a signal traveling between two points in the network. Thus, strictly speaking, the value represents “amplification” (which is typically less than 1) rather than “attenuation”, although we shall stick to the intuitively clear (albeit formally incorrect) name. Some other multipliers (factors) may be also applied to the signal, e.g., a boost by the specific sensitivity of the receiver (page 23), or a rate specific boost (page 16), but the attenuation “boost” (which in all sane circumstances is always rather strongly less than 1, or negative when expressed in dB) is the most important transformation that happens to a signal on its way from the sender to the recipient.

4.3.3 The sampled propagation model

The idea behind this kind of model is to replace the blanket attenuation formula, whose sole input is the distance between the sender and the receiver, with samples collected from the environment. As the coverage by samples can seldom be exhaustive, the model provides a fallback method to derive attenuation from distance, but in all those cases when a given



sender-receiver case reasonably well matches some sample(s), those samples take precedence.

The model is selected by setting the *type* attribute of <propagation> to *sampled*. The following example illustrates one way to declare a sample-driven propagation model:

```
<propagation type="sampled" samples="sfile.txt" sigma="1.5dB"
  average="4,0.1" symmetric="no">
  Distance-based attenuation table
    0.1m   -30.0dB
    1.0m   -32.0dB
    50.0m  -80.0dB
    100.0m -102.0dB
    150.0m -150.0dB
</propagation>
```

The <propagation> element provides an interpolated table to be used for straightforward transformation of distance into attenuation in those cases when samples cannot help. The procedure is in fact more involved and provides for a smooth and seamless transition between the samples and the distance-attenuation table, depending on how close (or far) the samples are from the current sender-receiver pair.

The actual samples are supplied in a separate file whose name is specified in the *samples* attribute of <propagation>. Note that this attribute is optional. If there is no file and no samples, then the distance-to-attenuation table is all there is and the model boils down to a table-driven, distance-based attenuation scheme akin to the shadowing model. Note that this scheme is more flexible than the shadowing model, because the table is not nailed to any particular formula (and may reflect measurements in some real-life area). Thus, the model can still be sample-driven in some sense.

The *sigma* attribute plays a role similar to its counterpart from the shadowing model providing a default randomization component of the attenuation. In the special case without samples, the attenuation is determined as:

$$ATT_{dB} = ATTB(d) + X(\sigma_{dB})$$

where $ATTB(d)$ is the interpolated attenuation level obtained from the table for the distance d , and σ_{dB} is the value of attribute *sigma* (X is the Gaussian distribution centered around zero with the mean of σ_{dB}).

If the *sigma* attribute is missing, it is assumed to be distance-specific. In such a case, the attenuation table is assumed to consist of triplets with the third number in every row providing the value of σ_{dB} for the given distance, e.g.,

```
<propagation type="sampled" samples="sfile.txt" average="4,0.1"
  symmetric="no">
  Distance-based attenuation table
    0.1m   -30.0dB   1.0dB
    1.0m   -32.0dB   3.0dB
    50.0m  -80.0dB   5.0dB
    100.0m -102.0dB  8.0dB
    150.0m -150.0dB 10.0dB
</propagation>
```

The actual values of σ_{dB} to be used for randomizing the attenuation calculated from the table are interpolated, in the same way as the base attenuation values.

The file with samples should consist of lines containing numbers. Empty lines, as well as lines starting with # (comments) are ignored. Otherwise, a line should contain either five or six numbers, the first four numbers are floating point and represent the coordinates of source and destination, the fifth number is an integer RSSI reading, and the optional sixth number indicates the transmission power at which the sample was collected. For example, here is one such line:



12.45 76.1 200.0 44.55 67

The sample was collected for a packet transmitted from a node located at coordinates $x=12.45$, $y=76.1$ (in distance units, i.e., meters) to a node at $x=200.0$, $y=44.55$ and the RSSI reading of that sample at the recipient was 67. There is no indication of transmission power; in such a case, the default power setting equal to the maximum setting from the <power> table (page 16) is assumed.

The numbers can be mixed with non-numeric text, which is ignored when the sample is read. For example, the above line could be written as:

XA=12.45 YA=76.1 XB=200.0 YB=44.55 RSSI=67

Note that every sample of this form can be interpreted as an attenuation case of a signal transmitted from some point A (the first pair of coordinates) to point B (the second pair). To transform the sample into the attenuation, one needs to consult the <rss> table (page 16) to convert the RSSI reading into the signal level at the recipient and then divide that signal level by the transmission power of the sample (or subtract the two levels, if calculating in dB).

A sample read from the file is preprocessed by the simulator. In particular, the four coordinates are transformed into internal distance units, i.e., converted to ITU (Section 4.2). This way they are also discretized into the network grid. Multiple samples whose sender-recipient points fall into the same grid squares are merged into one (note that it is also quite natural to collect multiple readings for the same pair of points). The RSSI of such a merged sample is the simple average of all the contributing RSSI readings. The standard deviation of those readings is also calculated and stored within the merged sample as the *sigma* to randomize the attenuation value produced from the sample. A sample consisting of a single reading will use the value of *sigma* derived from the distance, as if the attenuation was determined solely by the table.

If the *symmetric* attribute of <propagation> is yes, the channel is assumed to behave symmetrically, meaning that the ordering of the two end-points of a sample doesn't matter. In other words, the sample is going to fit a particular sender-recipient scenario as long as the two nodes occupy the same two points without telling which one is which. Otherwise, including the case when the symmetric attribute is not specified at all, the channel is deemed non-symmetric and the ordering of the two points is essential. Note that in the former case, these two lines in the data file:

30.0 60.0 40.0 70.0 190
40.0 70.0 30.0 60.0 192

will be merged into a single sample, while in the latter they won't.

A preprocessed sample (being a possible merge of several samples) is stored as the following record:

$$\{X_a, Y_a, X_b, Y_b, ATT, \sigma\}$$

where X_a, Y_a, X_b, Y_b are the coordinates of the two points, *ATT* is the attenuation factor, and σ is the mean for Gaussian randomization.

Below we outline the procedure for producing signal attenuation for a transmission from an arbitrary point *S* to an arbitrary point *R*. Note that we mean the basic attenuation factor (for which the propagation component of the channel model is responsible). Other factors (boosts) may be applied to the received signal level in some circumstances (see Section 4.3.1). Those factors are unrelated to the propagation model.

Note that if the two points *S* and *R* exactly match some sample, the answer is straightforward: the attenuation value is taken directly from that sample and randomized by $X(\sigma)$. If there is no perfect match, the model performs some rather complicated averaging whose objectives are:



1. to give priority (higher impact) to close samples
2. to account for the actual distance between the points S and R , if there is no close match by samples
3. to produce the obvious answer for the exact match naturally, without considering that situation as a special case

To appreciate point 2, note that (by definition) samples can only refer to packets that have been received, while the attenuation algorithm must produce a factor for basically any potential case of S and R separated by less than the cutoff range (page 14), which may happen to be much too distant for a successful transmission. Any average attenuation produced from the closest samples will always produce a “receivable” signal level and will make no sense when the distance between S and R exceeds the transmission range. In other words, if the samples are not too close, we should be factoring in the distance between S and R .

For 3, we would like to make sure that the averaging scheme is smooth, continuous, and seamless, and it automatically produces the right solution when the situation happens to fit the simplest and most obvious case. This should be an important sanity criterion for any complex scheme based on averages and weights.

Given S and R with coordinates X_s, Y_s, X_r, Y_r the procedure starts by locating K closest samples, where K is the first of the two numbers provided by the *average* attribute of <propagation> (see page 18). The distance of sample i from the pair of points S and R is captured by this measure:

$$d_i = \sqrt{(X_a^i - X_s)^2 + (Y_a^i - Y_s)^2} + \sqrt{(X_b^i - X_d)^2 + (Y_b^i - Y_d)^2}$$

i.e., it is the sum of the Euclidean distances between the starting and ending points. If the channel is symmetric, the distance is the minimum of d_i and:

$$\bar{d}_i = \sqrt{(X_b^i - X_s)^2 + (Y_b^i - Y_s)^2} + \sqrt{(X_a^i - X_d)^2 + (Y_a^i - Y_d)^2}$$

i.e., the same distance calculated for the two points of the sample switched. Then, the distances of the K selected samples are transformed into preliminary weights according to this formula:

$$u_i = e^{-\frac{d_i \times \alpha}{d_{avg}}}$$

where d_{avg} is the straightforward average of all K d_i 's and α is the factor appearing as the second number in the *average* attribute of <propagation>. The role of this transformation is to exponentially amplify small distances and to invert them into large weights (i.e., the larger the weight, the smaller the sample's distance from the case). Note that the weights are not normalized yet. Before that happens, they undergo one more transformation:

$$w_i = u_i \times \prod_{j \neq i} (1 - u_j)$$

whose primary goal is to make sure that in the case of a perfect match to some sample, only the weight of that sample becomes nonzero (with all the other weights vanishing). In the next step the weights are normalized:

$$W_i = \frac{w_i}{\sum_j w_j}$$

and used to calculate these averages:



$$\begin{aligned}
 ATT_{avg} &= \sum_i W_i \times ATT_i \\
 \sigma_{avg} &= \sum_i W_i \times \sigma_i \\
 D_{avg} &= \sum_i W_i \times D_i
 \end{aligned}$$

where D_i is the straightforward (Euclidean) distance between the two points of sample i . Finally, the attenuation for points S and R is calculated as:

$$ATT_{SR} = ATT_{avg} \times \frac{ATTB(D_{SR})}{ATTB(D_{avg})} + X(\sigma_{avg})$$

where D_{SR} is the Euclidean distance between points S and R . The last step scales the attenuation to the actual distance between S and R . Note that for a perfect fit $D_{avg} = D_{SR}$ and the scaling factor becomes 1.

Needless to say, the calculations are rather complicated and time consuming, because the first step involves scanning all samples while looking for K best matches. Therefore, the computed values ATT_{SR} and σ_{avg} are subsequently stored in a hash table for a quick lookup the next time they are needed. The table is hashed by a function of the grid coordinates of points S and R .

The parameters K and α specified in the *average* attribute of <propagation> default to 4 and 1, respectively.

4.3.4 The neutrino model

This is an unrealistic propagation scheme intended for special applications of VUE² models where there is absolutely no interference and the bit error rate is zero. The limitations for packet reception are purely formal (unrelated to propagation, attenuation, etc.) and boil down to:

- The optional range (distance) limit: it is possible to define a sharp “propagation distance” of the model beyond which the reception is zero, and below which the reception is 100%.
- The channel number: there is no cross-channel reception with channel separation being always perfect.
- The transmission rate: the rate of the receiver must agree with the packet's transmission rate, otherwise there is no reception (and no interference).

Note that transmission rates and distances (translating into finite reception and propagation times) are honored by the neutrino model. Thus the timing of actions involved in exchanging a single undisturbed and received packet across a given distance is going to look (almost) the same in the neutrino channel as in, say, the shadowing model, one difference being the lack of any LBT delay before the transmission attempt (it makes no sense to avoid an interference that cannot possibly happen).

The model is selected by setting the *type* attribute of <propagation> to *neutrino*. There is just one additional (and optional) attribute of <propagation>, and the body of the the element is ignored. Here is an example:

```
<propagation type="neutrino" range="100m"/>
```

In this case, the range limit is defined and equal to 100 meters. If the *range* attribute is absent, there is no range limit.



Many parameters of the generic channel model are ignored with neutrino-type propagation, specifically: the *bn* attribute of <channel> (the background noise), the elements <cutoff>, <power>, <rsssi>, and the minimum preamble length (*syncbits*). The propagation time is still modeled accurately, i.e., it takes the same amount of time for a packet to propagate a given distance as in a regular RF propagation model.

As the role of the neutrino model is to replace the more realistic models in special circumstances (perhaps temporarily and incidentally), the model accepts the parameters that it ignores without errors (so changes to data sets can be kept at minimum). This extends over dynamic modifications of those parameters by nodes, e.g., a node can change its transmission power setting (or rather think it has changed that setting), whereas the change has no impact on the channel's behavior (the power setting is ignored by the propagation model). Consequently, when you replace the <propagation> element in your channel model (changing it to neutrino), you need not edit any other elements/attributes in the data.

4.4 Nodes

This element describes the configuration of nodes in the network. Each of its sub-elements, except <defaults>, provides a set of parameters for one specific node. The expected contents of <defaults> are the same as for <node> and describe the default setting of parameters for all nodes. If a given parameter is not explicitly mentioned within a <node> element, its <defaults> setting is assumed for the corresponding node.

4.4.1 Node identification

A <node> element accepts a number of optional attributes. One of them is *hid* specifying the node's host ID as an unsigned lword-type number (which is usually specified in hex). This is the value that will be presented to the praxis in the *host_id* constant. Its intended interpretation is as a serial number of the node with the less significant 16-bit word used as the node's "local host ID", i.e., network address. Generally, the local host ID (if the *hid* attribute is specified) takes over the role of the node's identifier whenever node-related information is presented, e.g., by *udaemon* (see Section 7). Note however, that formally *hids* (host ID attributes) of different nodes need not be different (even though they normally are), which may occasionally lead to a confusion. Thus, in some cases, in particular when explicitly identifying a node for the model's input, or when writing the model's output to a file (as opposed to showing it in *udaemon*'s window), serial (SMURPH) node numbers are used (see below).

The serial number of a node is usually assigned implicitly (reflecting the order of node definitions in the data file), but it can also be assigned explicitly with another (optional) <node> attribute: *index* (a.k.a. *number*).¹⁵ The node numbers are internal SMURPH identifiers of the SIDE "stations" implementing the nodes. Although, in principle, nodes can be specified in any order in the data file, the resultant numbering of nodes must be continuous and start from zero. The total number of node definitions (<node> elements) in a data set must be equal to the *nodes* attribute of <network> (see page 10). The host ID of a node that defines no explicit *hid* attribute defaults to the node's SMURPH number (which is always well defined).

An explicit *index/number* attribute of a <node> element, if present, makes it obvious how to match the definition to an actual node number in the network model. If the attribute is absent, it is assumed that the definition has an implicit *index* attribute equal to the index of the previous definition + 1. If the first <node> definition has no *index* attribute, it is assumed to refer to node 0. Thus, in the most natural case, there is no need to reference node indexes (numbers) at all: the nodes are assigned numbers from 0 up, in the order of their appearance in the data set. Note, however, that it is legal for the data set to contain non-contiguous chunks of node definitions. To be correct, they should jointly exhaust all node numbers (between 0 and *nodes*-1) and do not attempt to describe the same node more than once.

¹⁵ These are two alternative names of the same attribute.



Another attribute of <node> is type which is only applicable to multiprogram praxes. It specifies the program label (see [7], Section 5) identifying the program run by the node. A type attribute appearing in <defaults> gives the default node type – to be assumed for a node that doesn't specify its type explicitly.

4.4.2 Initial state

The optional start attribute of <node>, which is also applicable to <defaults>, can be “on” or “off”, with “on” being the default. If start is “off”, then the node will not be started automatically. Such a node will have to be started explicitly, either from a panel process (described by a <panel> element in the input data, see Section 4.16) or by an external agent (connecting to the PANEL interface, see Sections 6.10 and 7.7). The start attribute of <defaults> specifies the default initial state of every node that doesn't specify its state explicitly.

4.4.3 Memory size

The amount of memory (RAM) available at the node for malloc is declared within this element (which should appear within <node>):

```
<memory> memory_size_in_bytes </memory>
```

The specified number should in principle match the physical size of RAM at the microcontroller minus the combined size of global variables (with provision for alignment). In a real-life program, PicOS reports this amount upon startup as the so-called leftover RAM.

4.4.4 Process number limit

This element:

```
<processes> process_number_limit </processes>
```

declares the size of the process table, i.e., sets the limit on the maximum number of PicOS processes that may be present at the same time. If the element is absent, there is no explicit limit on the number of processes. Note that most node programs use a decent (and bounded or fixed) number of processes, to this limit need not be specified, except when testing for runaway forks or similar exotic problems.

4.4.5 Radio interface components

If a node is equipped with a radio interface, then its declaration (or <defaults>) should include a <radio> element, which, in turn, should define the following items (see the <radio> element in <defaults> on page 11):

```
<power> power_index </power>
```

This element declares the initial setting of the transmission power with reference to the <power> table specified for the channel. The value must be in the index range of the first column of the channel's <power> table. If the element is missing, the lowest index from the <power> table is assumed by default.

```
<rate> rate_index </rate>
```

This element declares the initial setting of the transmission rate according to the <rate> table for the channel. The value must be in the index range of the first column of the channel's <rate> table. If the element is missing, the lowest index from the <rate> table is assumed.

```
<channel> channel_number </channel>
```

This element declares the initial channel setting for the RF module. The value must be a valid channel number according to the <channels> specification for the channel. If the element is missing, channel 0 is assumed by default.

```
<boost> receiver_gain </boost>
```



This element declares the receiver gain (boost) in dB, which is 0.0dB by default. A nonzero boost may correspond, e.g., to a special antenna employed at the node.

```
<preamble> preamble_length </preamble>
```

This element specifies the length (in physical bits) of the packet preamble to be inserted by the node's transmitter in front of every packet.

```
<lbt> delay threshold ... threshold tries </lbt>
```

```
<backoff> minimum span </backoff>
```

These parameters are used by the collision avoidance procedure of the node's transmitter and roughly correspond to the similar parameters used by our real-life radio drivers, notably CC1100 and CC430.

The <lbt> element includes a list of numbers referring to the LBT (Listen Before Transmit) action. The first and the last values are unsigned integers, the values in between are interpreted as (floating point) signal thresholds (in dBm).¹⁶

The first number specifies the time interval (in milliseconds) during which the transmitter will pause before a spontaneous transmission while monitoring the received signal level. If the maximum signal level noticed during the delay turns out to be above a threshold, the transmitter will back off (according to the <backoff> specification) and try again later. The last value in <lbt> tells how many such attempts should be made before forcing the transmission. Each attempt will use its own threshold value from the specified list. For example, with this specification:

```
<lbt> 1 -110.0 -100.0 -90.0 -80.0 4 </lbt>
```

there will be up to 4 attempts to yield to a detected signal at the increasing thresholds of -110, -100, -90, and -80 dBm. The fifth attempt will be forced regardless of whether the node perceives any activity or not.

The number of thresholds can be less than the number of tries (but not the other way around). In such a case, the last threshold will be used for all the remaining attempts.

If the <lbt> element is empty, or if the delay value is 0 (in that case the element may contain a single value), the LBT procedure is disabled, which means that the node will transmit immediately as soon as an outgoing packet becomes ready.

The back-off delay after a failed attempt is described by the two integer values in the <backoff> element. The delay is a random number between minimum and minimum+span-1 rounded to an integer number of milliseconds. Thus, for example, if minimum is 2 and span is 63, the backoff delay will be uniformly distributed between 2 and 64 (PicOS) milliseconds, inclusively.

The total number of nodes whose specification includes a <radio> element must match the number of nodes declared with the <network> element as being equipped with a radio interface. Note that this is usually the total number of nodes in the network, unless the <network> element has a non-trivial radio attribute. If the <default> element specifies a radio interface (has a <radio> sub-element), then any node devoid of an explicit <radio> element is automatically assigned the default specification. If you want to explicitly indicate that a particular node has *no* radio interface, use an empty <radio> element, e.g.,

```
<radio></radio>
```

This element is mandatory for a node equipped with a radio interface:

```
<location> ... x ... y ... </location>
```

¹⁶ The somewhat obscure format of the element results from the need for backward compatibility with older data sets where the specification consisted of exactly three numbers: delay, single threshold, and try count.



and it must be explicitly present in every such a <node> (no defaults). The element assigns a location to the node as a pair of coordinates in meters (floating point numbers). The coordinates can be arbitrary as long as they are non-negative. Nodes can only be deployed in the right upper quarter of the infinite Cartesian plane.

One optional attribute of the <location> element is movable whose legal values are “yes” and “no”, with “yes” being the default. A movable node can have its location changed, e.g., in response to a request from an external agent, or by a roamer (see Section 4.15). A non-movable node is nailed to its fixed position declared with the <location> element.

A radio-less node need not have its location specified (although it isn't forbidden). The default location of such a node (if queried) is (0.0, 0.0).

The coordinates of a <location> element appearing in <default> are ignored; however, you can use the movable attribute of that element to change the movability default, e.g.,

```
<defaults>
...
<location movable="no"/>
...
</defaults>
```

says that no node is movable unless its <node> element explicitly says otherwise, e.g.,

```
<node>
...
<location movable="yes"> 2.5 7.45 </location>
...
</node>
```

Note that node locations can be removed from <node> elements and specified in a separate data block (Section 4.4.7) to make it easy to replace them without affecting any other components of the data set.

The following compound <node> sub-elements are optional (they apply to the various optional modules/interfaces that can be present or absent at any node): <uart>, <pins>, <leds>, <emul>, <ptracker>, <eprom>, <iflash>, <preinit>. These elements are discussed in sections 4.5 through 4.14.

4.4.6 Supplementary node specifications

The simulator may receive supplementary node data, potentially in multiple separate files, to be interpreted as one or more default layouts for nodes. This feature is intended to facilitate storing node layouts separately from other components of data sets, e.g., associating them with board descriptions. The way to pass such layouts to the simulator is described in Section 5. Normally this is done automatically by PIP when it spots a file named node.xml in a board directory associated with the project. Such a file should contain a single XML element named <node> whose contents are parsed in the same way as <defaults> occurring inside <nodes>. The definition provides an alternative default layout of a node whose type qualifies it to the particular board.

When parsing a regular <node> definition, the simulator first looks at the node type attribute (Section 4.4.1) to identify the board matching the node. For a single-program praxis, the issue is trivial: there is a single board and a single node type (all nodes are qualified to the same board). If no node layout is available for the board (the board directory has no node.xml file), the node components that are not mentioned explicitly are inherited from the <defaults> layout in the regular data file (if one is present). Otherwise, the board-specific layout is used instead of <defaults>.

To make it all a bit safer (considering that the board configuration for the project is not manifest in the data set), the fallback to the respective default is controlled by a special <node> attribute. That attribute is named default and works as follows:



1. If the value of default is "flexible", then the board-specific default will be used if available, and the regular default will be used otherwise.
2. If the value of default is "board", then the board-specific default must be available (and it will be used), otherwise, an error will be signaled.
3. If the value of default is "default", then the board-specific default will be ignored (only the regular default will be used, if present).
4. If the attribute is absent, it defaults to "default". This is for safety and backward compatibility of old data sets.

Here is an example:

```
<node number="3" default="board">
  <location>1.5 4.3</location>
</node>
```

which defines a node whose layout is completely determined by the board's node.xml file, except for the location, which must be specified individually for every actual node. Note that the board-specific layout must be present: the definition will not fall back to <defaults> in the standard data set.

4.4.7 Separating node location information

To facilitate modifying node locations, including saving node locations after rearranging the configuration of nodes in the ROAMER window (Section 7.6), the location information of nodes can be separated into a single XML element which can be conveniently included from a self-contained file (Section 4.17). For illustration, a data file fragment looking like this:

```
<nodes>
  <defaults>
    ...
  </defaults>
  <node>
    ...
    <location> 10.0 15.0 </location>
  </node>
  <node>
    ...
    <location> 20.0 25.0 </location>
  </node>
  <node>
    ...
    <location> 30.0 35.0 </location>
  </node>
</nodes>
```

can be rewritten as:

```
<nodes>
  <defaults>
    ...
  </defaults>
  <node>
    ...

  </node>
  <node>
    ...

  </node>
```



```

<node>
...

</node>
<locations>
    <location> 10.0 15.0 </location>
    <location> 20.0 25.0 </location>
    <location> 30.0 35.0 </location>
</locations>
</nodes>

```

The items from the <locations> element (note that it must belong to <nodes>) are matched to the consecutive nodes. A location specification can include an explicit reference to its node number, e.g.,

```
<location index="2"> 10.0 15.0 </location>
```

assigning it to a specific node regardless of its ordering in the list. The same rules apply as to the index/number attribute of a <node> element (Section 4.4.1). Here the index attribute can also occur as number, e.g.,

```
<location number="2"> 10.0 15.0 </location>
```

is exactly equivalent to the previous specification.

A <location> element in the <locations> list can also specify the movable attribute, in exactly the same way as for the corresponding element on <node> (Section 4.4.3).

A location specification associated directly with <node> (Section 4.4.3) takes precedence over the <locations> list. Note that the list need not be complete, i.e., cover all nodes. The way to determine the movable attribute is to start from the internal specification (the one occurring at <node>, if any). If that specification defines movable, then it is assumed. Otherwise, the node's entry in the <locations> list is consulted, if present. If it specifies movable, then the specification becomes valid for the node (node that the location coordinates are taken from the local specification, if present). Finally, the default node specification is checked (which may come from <defaults> or from the supplementary file associated with the board (Section 4.4.6).

4.5 The UART

Each node may be optionally equipped with a UART, whose functionality, as perceived by the praxis, accurately mimics two most popular ways of accessing the UART in PicOS: 1) direct interface (operations *ser_in*, *ser_inf*, *ser_out*, *ser_outf*, *ser_outb*) [1], and 2) packet-style interface with the UART being viewed as a PHY for VNETI (TCV) (modes 'N', 'P', 'L', 'E', and 'F' described in [8]). This option is selected with the mode attribute of the <uart> element, which can be one of the following:

"direct"	(or "d")	selecting the default direct interface to the UART
"npacket"	(or "n")	selecting the 'N' mode interface over VNETI
"ppacket"	(or "p")	selecting the 'P' mode interface over VNETI
"line"	(or "l")	selecting the 'L' mode (line) interface over VNETI
"escape"	(or "e")	selecting the 'E' mode interface over VNETI
"fscape"	(or "f")	selecting the 'F' mode interface over VNETI

With the direct mode, the praxis can access the UART via the collection of *ser_...* operations listed above. With the packet mode, the praxis can open the UART PHY by executing *phys_uart* [8]. Then it can associate a plugin with the UART PHY and use the interface essentially in the same way as an RF module. Finally, the line ('L') mode makes it possible to use the VNETI packet interface with a straightforward ASCII-oriented appearance of the UART at the other end [8].



The UART description in the input data assigns a bit rate to the UART, declares the sizes of two buffers to be used by the driver model, and determines what happens to the output and where the input will be coming from. The first three values are provided as attributes of `<uart>`, e.g.,

```
<uart rate="9600" bsize="12,8">
```

with the rate attribute being mandatory and bsize being optional. The first of the two bsize numbers gives the length of the input buffer,¹⁷ and the second one declares the size of the output buffer. The default buffer size is 0 (in both cases), which effectively corresponds to “no buffer.”¹⁸ This is assumed for both buffers, if no bsize attribute is present in `<uart>`, or for the output buffer, if only one number is provided, e.g.,

```
<uart rate="9600" bsize="12">
```

The UART's interface to the real world is described by the `<input>` and `<output>` elements. The options are:

4.5.1 Local file or device

```
<input source="device">device or file name</input>  
<output target="device">device or file name</output>
```

The body of each element is stripped of any initial and trailing white spaces and the remainder is interpreted as a file name path relative to the directory where the model (the side program) has been invoked.

If the names refer to files (rather than devices) then they should be different to make sense. On the other hand, they may represent the same device, e.g., a TTY terminal window. In that case, the UART may directly interact with the user.

The (input) characters arriving from a file/device, as well as those written by the praxis to the UART and sent to a file/device, are not preprocessed in any way (using the UNIX terminology, we would say that the interface is “raw”). The assumed interpretation of lines in PicOS, for the ASCII-oriented UART access functions `ser_out`, `ser_outf`, `ser_in`, `ser_inf`, is that an output line ends with CR+LF, and an input line must end with at least one of those characters, with any sequence of CR and/or LF characters at the end interpreted as a single end of line.

Both `<input>` and output elements accept an optional coding attribute, which can be “hex” or “ascii”, with “ascii” being the default, e.g.,

```
<input source="device" coding="hex">
```

With the “hex” coding, the input is assumed to be a sequence of bytes expressed as pairs of hexadecimal digits. Whenever a next byte is read from the UART, the emulator will look up in the file the next character looking like a hexadecimal digit (skipping all other characters). Then, if the following character is also a hexadecimal digit, the two will be decoded into a byte and returned as the read character. Otherwise, the program will be aborted with an error message. For output, the “hex” coding produces a sequence of 2-digit hexadecimal representations of the output bytes separated by spaces.

The `<input>` element accepts an optional type attribute, whose value can be “timed” or “untimed”, with the latter being the default, e.g.,

```
<input source="device" type="timed">
```

For the “timed” type of input, the input file must be organized into records looking like this:

¹⁷ This corresponds to a compilation parameter for PicOS.

¹⁸ In fact a single-byte buffer is used by the model in that case, which corresponds to the hardware UART register on the microcontroller. This has the same meaning as the buffer size of zero in PicOS. Also, the MSP430 UART driver in PicOS uses 0 for the output buffer size (there is no parameter to change that).



```
time { input_data }
```

where time is a floating point number describing the time when the record will become available for input. If preceded by a '+' sign, the number describes the interval in seconds from the availability time of the previous record (or from 0 if the record starts the input sequence). If there is no '+', the number represents absolute time in seconds from the beginning of run (time 0). If the time has already passed when the record is looked at by the system (i.e., the processing of previous records took more time than the record's availability time), the record becomes available immediately.

Once a record becomes available, its characters will arrive at the UART at the nominal rate specified in the <uart> element. If the praxis does not retrieve them on time, they will be lost. This is different from the "untimed" (default) operation whereby the bytes to be read by the praxis patiently await acceptance. In that case, the UART rate only determines how fast they can be extracted (the minimum space between characters), but they never arrive faster than the praxis can handle them.

Here is an example of a timed input sequence:

```
5.0 {s 4096\r\n} +4.0 {r\r\n} 3600 {s 0\r\n}
```

The string within braces may not include a closing brace unless escaped with a backslash. Generally, any character can be escaped with a backslash (including the backslash itself, which must be escaped). The escapes `\r`, `\n` and `\t` are treated as special characters (the last one standing for a TAB). An explicit newline also stands for itself, i.e., is equivalent to `\n`.

The timed mode can be combined with "hex" coding, e.g.,

```
5.0 {73 20 34 30 39 36 0d 0a}  
+4.0 {72 0d 0a} 3600 {73 20 30 0d 0a}
```

is equivalent to the previous sequence under "hex" coding.

4.5.2 Short input sequence specified directly in the data file

The source attribute of <input> can be "string", e.g.,

```
<input source="string">a direct sequence of bytes</input>
```

This specification is most useful in those circumstances when the node expects some short input from the UART at the beginning, e.g., to initialize the praxis. Generally, if the input part of the UART file is reasonably short, it can be inserted directly into the body of the <input> element, e.g.,

```
<input source="string">s 4096\r\n</input>
```

The XML parser of SMURPH removes the leading and trailing white-spaces from the string (this applies as a blanket rule to all items). Thus, this alternative version of the above sequence:

```
<input source="string">  
s 4096  
</input>
```

would not work (the command would not be properly terminated as a line).

The output end of a UART with "string" input may still be assigned independently to a file/device. Also, the "string" source can be combined with "hex" coding and/or "timed" mode, e.g.,

```
<input source="string" type="hex" mode="timed">  
5.0 {73 20 34 30 39 36 0d 0a}  
+4.0 {72 0d 0a}  
3600 {73 20 30 0d 0a}  
</input>
```



Defining a <default> UART whose input is mapped to a file is usually not a good idea, even if it works in principle. This is because, for a large network, the multiple instances of the file being opened for different nodes may deplete the population of allowable file descriptors and crash the model. On the other hand, having a default UART with an immediate input string (say for a default initialization of all the nodes) makes perfect sense. The output part of such an UART can be legitimately left unspecified.

Needless to say, the above ways of providing external input to a UART, or absorbing its output, are not very convenient (in fact they are practically useless) in a packet mode (Section 4.5). Typically, in such a case, the praxis wants to talk to some OSS program implementing some non-trivial protocol. The proper way of handling this kind of interaction is to direct the modeled UART to an external agent (like *udaemon* – see Section 7) providing a link between the virtual world of the VUE² model and the real-life OSS program. PicOS terminal emulator, *ptiter*, offers a shortcut for a direct connection to a UART model in VUE² [8].

4.5.3 Remote association through an agent

The most flexible option is to map the UART to a socket and make it possible for external agents to claim its input and output. This is accomplished by using “socket” for the source and target, e.g.,

```
<input source="socket"></input>
<output target="socket"></output>
```

Once you map one end (say input) to a socket, the other end (output) also becomes mapped to a socket (there is no way to map it differently). Thus, the second line in the above sequence is redundant (although harmless). It may still be needed, if some other attribute of the element must be included, e.g., *coding="hex"*. A specification like this:

```
<input source="device">/dev/tty</input>
<output target="socket"></output>
```

will produce an error.

The body of an <input> or <output> element specifying “socket” is always ignored. External agents connect to such a UART following a special protocol that identifies the node (see Section 6.2). Thus, there is no need to provide any more details at this stage. A socket input can also be “hex” and/or “timed”. A socket output can be “hex”. Additionally, an <output> element specifying *target="socket"* may also include *type="held"* among its attributes, e.g.,

```
<output target="socket" type="held"></output>
```

The meaning of this setting is that the initial output written to the socket is saved and will be presented to the agent upon its (first) connection. This way you can make sure that whatever the praxis writes to the UART is never lost. This is important because before an agent can connect to the socket, the model must be started; thus, if the node writes something to the UART immediately after startup, that output would be inaccessible without the held option.

4.5.4 Partially mapped UARTs

A socket UART is flexible in the sense that an agent may connect to it and disconnect many times. If anything is written to the UART while no agent is connected to it (excepting the period preceding the first connection to a held socket), that output is discarded and lost. Also if the node tries to read something from a disconnected socket, it will simply receive no data. This is the same as for a real UART with no data available.

For a device-mapped UART, and also for a UART whose input end is mapped to a string, it is legal to leave one end unmapped. For example, when writing to a UART whose output end is unmapped (but the UART is present), the output will be absorbed by the UART and discarded. An attempt to read from a UART with no input end will never return any data, but is formally legal. On the other hand, if no UART is defined at all, any attempt to reference it for I/O will trigger an error and abort the model.



You can indicate explicitly that the particular UART end is unmapped by saying something like this:

```
<output target="none"></output>
```

This is equivalent to simply skipping the specification. Note that a socket UART always defines two ends, even if only one end is explicitly mentioned in the declaration.

If a <node> element has no <uart> sub-element, but there is such a sub-element in <default>, then the <default> specification of UART will be assumed by the node. If the node wants to say explicitly that it has no UART, default or otherwise, the following declaration should be used:

```
<uart></uart>
```

This is the only variant of the <uart> element that requires no rate specification.

Note that any empty specification of this kind can be shortened to:

```
<uart/>
```

4.6 The LEDS module

For a node equipped with LEDs, you can make their status traceable or presentable to external agents. Here is a sample declaration of the LEDS module within <node>:

```
<leds number="4">
  <output target="device">led_status.txt</output>
</leds>
```

It says that any updates to the LEDs will be written to file led_status.txt. Each update takes one ASCII line beginning with the letter U (capital) and terminated with the newline character. A complete line looks like this:

```
U T F LLLLL ... LLL
```

where T is the time of the status change in seconds (a floating point number), F is 1 or 0, depending on whether the fast blink option is active or not (see operation *fastblink* [1]), and each of the subsequent characters stands for the status of one LED from zero up (i.e., the length of the L...L string is equal to the number of LEDs). The values are: 0 – the LED is off, 1 – the LED is on, 2 – the LED is blinking. Here is an example:

```
U 10.325 0 0101
```

To make the LEDs status perceptible by external agents, use "socket" as the output target, e.g.,

```
<leds number="2"><output target="socket"></output></leds>
```

Having connected to the LEDS module via the socket interface, the agent will be receiving updates in the same format as if they were written to a file.

Note that a LEDS module description can be placed in <defaults>. It may not make a lot of sense to direct LEDs status updates of all nodes to the same file, but it is perfectly legal to declare that all nodes can have their LEDs inspected by an agent (target="socket"). If no agent is connected to the module, changes in the LEDs status trigger no external actions. Upon a connection, the agent will receive the current status of the LEDs, and then it will be receiving updates for as long as it remains connected.

Similar to UART, to explicitly say that a node has no LEDs (e.g., overriding the default), you can use this declaration:

```
<leds></leds>
```

Specifying zero as the number of LEDs has the same effect. In that case, the <output> specification is ignored if present.



4.7 The EMUL module

The role of this module is to provide for a generic output interface for hardware that has no specific VUE² model. For example, suppose that you are extending your praxis to incorporate a tentative node with an exotic LCD, and you don't want to spend time on developing a graphical model of that LCD. But you still want to have some (possibly crude) way of modeling the device, with the intention of developing a better model, should you decide to keep the LCD. A possible solution is provided by diag [1]; however, one problem with this function is that its VUE² variant writes its output to the (global) SIDE output file, which makes it difficult to trace the data interactively and quickly associate them with the respective nodes.

As perceived by the praxis, the EMUL interface looks similar to diag, except that its output can be sent to external agents and, in particular, displayed by udaemon (see Section 7) in a per-node window. The praxis calls this function:

```
void emul (sint type, const char *fmt, ...);
```

where the first argument is a short integer number intended to identify the emulated device (in case there is more than one handled this way), the second is a format string, and the remaining ones are the items to be encoded according to the format, e.g.,

```
emul (0, "display text: %s, in line %ld", lcd_str, lcd_ln);
```

Note that a line encoded with emul need no newline character at the end.

When compiled for PicOS, all references to emul are converted to NOPs by default. You may redefine them to whatever you desire (e.g., to diag) by putting a macro definition for emul into options.sys.

The way to handle emul calls by VUE² is described in the data file on a per-node basis. Here is an example:

```
<emul>
  <output target="device">emul_output.txt</output>
</emul>
```

It says that the lines produced by calls to emul will be written to the specified file. Generally, it makes better sense to direct them to a socket, e.g., like this:

```
<emul>
  <output target="socket"></output>
</emul>
```

Note that there is no <input> specification. With this declaration:

```
<output target="socket" type="held"></output>
```

you will make sure that any lines produced by calls to emul issued before the agent connects to the socket will be accumulated and presented (sent) upon connection. This will also happen when the agent disconnects and then connects again, i.e., no line produced by emul will ever be lost. You should be careful with this option when the amount of emul data can be large, as it may eat up the memory of the simulator. Note that, in contrast to EMUL, the held option applicable to the UART module (page 30) only holds the pending data before the first connection.

Similar to all other node-related components of the model, <emul> can appear in <defaults> (Section 4.4) as well as inside individual <node> specifications. If a node has no EMUL module (no applicable <emul> declaration), its calls to emul will be completely void. The way to individually cancel the global effect of a default <emul> (to disable the module for a specific node) is to put this:

```
<emul></emul>
```

or



<emul/>

into the respective <node> element.

When the emul output is directed to a file, the format of a line written with a single call to the function is:

<type> message

For example, this call:

```
emul (3, "Value %04x written to slot %1d", 12, 7);
```

will produce:

```
<3> Value 000c written to slot 7
```

Exactly the same lines, i.e., sequences of characters separated by newline characters (no NULL-byte sentinels) are sent to the external agent for socket output.

4.8 The PINS module

This module provides an external interface to the node's I/O pins, including ADC and DAC. The node-inflicted changes to the (output) pins can be sent to an agent or stored in a file. Similarly, external changes to the pin voltage can be submitted by an agent or read from a file, possibly along with their timing. Here is a sample declaration:

```
<pins total="10" adc="8" counter="1,8,8"
  notifier="2,8,256" dac="6,7">
  <output target="device">pins_output0.txt</output>
  <input source="device">pins_input0.txt</input>
  <status>111111111</status>
  <values>0000000000</values>
  <voltage>0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0</voltage>
</pins>
```

which is complex enough to illustrate all sub-elements that can possibly contribute to <pins>. Except for the trivial declaration <pins/>, which explicitly states that the node has no PINS module, the total attribute of <pins> is required, and it specifies the total number of I/O pins in the module. If the adc attribute is present, it declares the number of pins capable of providing input to the analog-to-digital converter. That number cannot be larger than total. The ADC-capable pins constitute an initial (number-wise) subset of all pins.

The conventions assumed for identification and access to the pins are strongly related to the standard pin interface [10] offered by PicOS (functions pin_read, pin_write, pin_read_adc, pin_write_dac, etc., including pulse monitor and notifier). Some familiarity with that interface will help you understand the ideas behind the PINS model.

If the PINS module is to be equipped with the pulse monitor, which consists of two pins: the counter and the notifier, the numbers of those pins can be specified with the optional counter and notifier attributes. The full specification of each of those pins takes up to three numbers. The first number identifies the pin, and must be less than the total number of pins, the remaining two values describe the "on" and "off" debouncing intervals expressed in milliseconds. Both, counter and notifier pins can be any pins, including those capable of ADC/DAC operation. Similar to PicOS, if the counter/notifier is not running (the function is switched off by the praxis), the respective pin can be used for its standard function.

The interpretation of the debouncing parameters is as follows. If the pin gets into the triggering state (depending on the edge setting, e.g., high for edge = 1), it must remain in this state for at least the "on" interval for the trigger to be considered valid. If the pin state changes within the "on" interval, the trigger is ignored. Similarly, once the trigger is successful, the pin must enter the opposite state for at least the "off" interval before it can trigger the next event. If a debouncing parameter is not specified (or is explicitly zero), the



corresponding phase of the action is not debounced. Note that it is legal to specify a single debouncing parameter (which will be interpreted as the “on” interval, with the “off” interval assumed zero). If no debouncing parameters are specified, they are both assumed to be zero.

If any pins should provide DAC output, their numbers can be specified with `dac`. Note that only some models of MSP430 offer this functionality, which is mostly confined to two hardware pins.

The role of `<status>` is to indicate whether any of the pins in the range 0 ... total-1 are absent, i.e., the range includes holes.¹⁹ The status of each pin is described by a single binary digit in the string, with 1 standing for “present” and 0 for “absent,” with the leftmost digit corresponding to pin 0. If no `<status>` element appears within `<pins>`, it is equivalent to “all ones,” i.e., no absent pins. If the string is shorter than the number of pins, the unaccounted for pins are all deemed present.

The `<values>` element assigns initial digital values to all pins, which can be 0 or 1. Note that this assignment is only meaningful if the praxis sets the pin to input. At this stage, the declaration is equivalent to pulling the physical pin down or up via a resistor. Note, however, that it can be changed dynamically through an agent or from an input file. If the specification is absent, the pin values default to all zeros. If the string is shorter than the number of pins, the unaccounted for pins are all pulled down (initialized to 0).

Similarly, `<voltages>` assigns predefined analog values to the ADC-capable pins – in the natural order. When such a pin is selected by the praxis for its ADC function, this is the constant voltage that will show up on the pin for conversion. Again, that voltage should be viewed as initial, because it can be changed by an agent or from an input file. If the specification is absent, the voltage defaults to all zeros. If the number of items in the list is less than the number of ADC-capable pins, the unaccounted for pins are set to voltage 0.

The `<input>` and `<output>` specifications are similar to those for UART, albeit simpler, because the elements take no attributes besides source and target. The string source option is also available. There is a way to set up timed scripts for configurations of pin values via explicit sequences in the input data.

An input command addressed to a pins module is an ASCII line starting with one of the letters T, S, and D. With a T command, you request a delay before reading the next command. The letter must be followed by a non-negative floating point number optionally preceded by a sign, e.g.,

```
T 12.5
T +0.01
```

In the first case, the number indicates the absolute time in seconds at which the next command should be read and interpreted. If the model is already past that time, the next command is read immediately. In the second case, the specified delay in seconds is calculated from the current moment.

An S command sets the digital value of a single pin. The letter is followed by the pin number in decimal followed in turn by 0 or 1, e.g.,

```
S 12 0
S 0 1
S 14 1
```

A D command assigns a voltage to the specified pin. The letter is followed by the pin number and the discretized voltage as a number from 0 to 32767 (0x7FFF) corresponding linearly to 0 ... 3.3V.²⁰

¹⁹ Even though the pin numbering is purely logical (defined on the per-board basis), the numbering convention assumed in PicOS makes it possible to exclude some pins from the continuous range.

²⁰ No negative voltage is implemented at present.



An integer number can be specified in decimal (in the natural way) or in hexadecimal preceded with 0x. Initial spaces preceding the command letter are ignored. Thus, for example, the following sequence of commands is OK:

```
T 0.5
S 0xc 1
S 0 0x0
D 0xf 0x00ff
T 1.0
D 0xf 0x0000
```

An immediate input string (the source="string" option) should look like the contents of a file with a series of input commands, with the command lines separated with explicit new lines or \n sequences, e.g.,

```
<input source="string">P 1 1\nP 2 1\nT 0.01\nP 2 0\n</input>
```

is equivalent to:

```
<input source="string">
  S 1 1
  S 2 1
  T 0.01
  S 2 0\n
</input>
```

Note that (according to what we said in Section 4.5.2), the last line must be explicitly ended with a (special) newline character, because the XML parser strips all white spaces from the string.

If the <output> part of the interface is configured and active, every change in the status of a pin results in an update message being written to the file or sent to the agent. Such a message starts with the letter U (capital) and consists of the following four components:

1. The time in seconds (with millisecond granularity) followed by a colon.
2. The number of the affected pin.
3. The status of this pin (a single decimal digit).
4. The pin value.

Here we have a few examples:

```
U 24.556: 4 1 0
U 3600.120: 7 3 176
U 2365.667: 2 0 0
```

The pin status value is interpreted as follows:

- 0 – digital input pin
- 1 – digital output pin
- 2 – an ADC pin
- 3 – the first DAC pin
- 4 – the seconds DAC pin
- 5 – pulse monitor counter pin
- 6 – pulse monitor notifier pin

The output value for cases 5 and 6 is always zero. For cases 2, 3, 4, the value is a number between 0 and 32767 representing the voltage (it is the output voltage for status 3 and 4, and the input voltage for status 2). For cases 0 and 1, the value can only be 0 or 1.

When the output is directed to a file, it starts with the complete list of initial pin values. From then on, the full status of all pins can be determined by tracking the updates reflecting changes in the individual pins. In the socket case, whenever an agent connects to the



module, it receives the standard node signature (see Section 6.1) immediately followed by an initial series of “updates” for all pins reflecting their current status and values.

4.9 Buttons

PicOS offers a standard interface to buttons, which are selected pins capable of triggering “button pressed” events. In VUE², buttons can be declared in the input data set, within the context of <pins>, such that pertinent changes in their voltage will translate into button pressed events perceptible by the praxis (the buttons_action function). Consider this sample declaration:

```
<pins number="7">
  <input source="socket"></input>
  <buttons polarity="low" timing="200">0 2 5 6</buttons>
  <values>1111111</values>
</pins>
```

With this declaration, pins number 0, 2, 5, and 6 of the total 7 pins (numbered 0 through 6) will be used as buttons (numbered 0 through 3). Their pressed status is low, and the single debounce parameter (200) stands for the minimum number of PicOS milliseconds separating two button-pressed events. The list of debounce values can include two more numbers: the initial delay (in milliseconds) before an automatic repeat (if the button remains pressed) and the repeat interval (also in milliseconds). If the first of these numbers is zero (or not specified), auto repeat is disabled. If the second number is zero (or absent), it is assumed to be the same as the first number.

The legitimate values of polarity are low, high, 0, 1 (the last two being alternatives for low and high), with high being the default. The numbering of buttons (as seen by the praxis) is always consecutive from zero up. The list of values in the body of <buttons> is interpreted as an array mapping indexes from zero up into pin numbers.

4.10 The SENSORS module

This module provides an external interface to the node's set of sensors and actuators, which are accessible by the praxis via the PicOS functions read_sensor and write_actuator. Here is a sample definition:

```
<sensors>
  <output target="device">actuator_output0.txt</output>
  <input source="device">sensor_input0.txt</input>
  <sensor index="0" vsize="2">398</sensor>
  <sensor vsize="1" delay="0.001"></sensor>
  <sensor vsize="3" delay="0.1,0.3" init="4">15</sensor>
  <sensor index="4">257</sensor>
  <actuator vsize="2" delay="1.0,2.0">4095</actuator>
  <sensor index="-1" vsize="2" init="2240">2300</sensor>
</sensors>
```

The <sensors> element has no attributes. The total number of sensors and/or actuators is determined from the element's contents and need not be announced. The arguments and definition layouts are the same for sensors and actuators.

All attributes of <sensor> and <actuator> are optional. The index attribute assigns a number to the sensor/actuator, which will identify it for the praxis (it corresponds to the second argument of read_sensor/write_actuator). If the index attribute is absent, the sensor/actuator will be assigned the next unused number. This is similar to the definition of nodes (Section 4.4), except that there can be no negative node numbers (while sensor/actuator numbers can be negative, as explained below). If the first sensor/actuator element has no index attribute, it is assumed to be zero. Note that sensors and actuators are numbered independently.



Sensor (and actuator) numbers (indexes) can be negative. The total number of sensors (actuators) is determined as $\text{max} - \text{min} + 1$, where max is the maximum sensor (actuator) index and min is the minimum sensor (actuator) index or zero, whichever is less. The indexes of sensors (actuators) defined in the data file need not cover a contiguous range, but each sensor (actuator) index can be used at most once. Nonexistent sensor (actuators) will trigger errors when referenced. Note that sensor number 3 in the above example does not exist, but sensor 4 is present. Holes like this may make little sense, but they are not illegal. The maximum number of all sensors (actuators) is 256 (separately for each class).

Negatively numbered sensors are intended to represent “hidden” (or special) sensors that are logistically different from the rest (the internal chip voltage sensor is one example). This way the “application” sensors can be numbered from zero, while the special sensors can also have a fixed range of numbers independent of the configuration of the application sensors.

Attribute *vsize* determines the size of the sensor/actuator value in bytes. Legal sizes are 1, 2, 3, and 4. The default size is 4, but, if the definition specifies a range (see below), and *vsize* is absent, the size will be determined from the range: as the smallest number of bytes needed to accommodate the maximum possible value stored in the sensor/actuator. In all cases, the value to be extracted from a sensor or stored in an actuator is interpreted as an unsigned integer (which is never negative).

Size 3 is discouraged and may never be used for a real sensor/actuator. While sizes 2 and 4 are interpreted as word and lword types in an endian-independent way, it is impossible to do the same for a 3-byte number. For now, such a number is interpreted as little-endian.

Attribute *init*, if present, provides an initial value for the sensor/actuator. If that value exceeds the declared range (see below), the maximum legal value is used. If the attribute is absent, the sensor/actuator is initialized to zero.

The delay attribute should consist of one or two (comma separated) floating point numbers. It describes the delay in seconds incurred in reading a value from the sensor (via *read_sensor*) or storing a value into the actuator (via *write_actuator*). If there are two numbers, then the delay will be generated as a random value between them (note that the second number must not be less than the first one). If the delay attribute is absent, operations on the sensor/actuator will incur no delays.

If the body of a <sensor> or <actuator> element contains a strictly positive integer number, that number is interpreted as the range, i.e., the maximum value that the sensor/actuator is able to assume. The minimum is always zero. If no range is specified, it is inferred from *vsize* as the maximum unsigned value that can be stored in the specified number of bytes. If neither *vsize* nor the range is present, then, by default, the size is assumed to be 4 and the range is $2^{32}-1$.

The <input> and <output> specifications are exactly the same as for PINS. If the input is from a socket, then the output is implicitly assumed to be present and directed to the same socket. As for all other types of objects, it is illegal to associate one direction with a socket and the other with something else.

An input command addressed to the module is an ASCII line starting with one of the letters T, S, or E. Similar to PINS, a T command requests a delay before reading the next command. An S command has this syntax:

S sn v

where *sn* is the sensor number (index) and *v* its new value. The rules for encoding numbers are as for PINS.

An E command takes a sensor index as the only argument, i.e.:

E sn



It triggers a sensor event on the indicated sensor, which can be awaited (on the praxis's side) with `wait_sensor`.

Here is a sample sequence of commands:

```
T 0.5
S 0 223
S 1 0xffe
T +1.0
S 0x2 19999
E 2
```

If the <output> part of the interface is configured and active, every change in the value of an actuator results in a message being written to the file or sent to the agent over the socket. If the connection is over a socket (as opposed to a device), then, additionally, every change in the value of a sensor results in a similar message. The latter can be used by the remote agent as an acknowledgment of its last S request.

The output always starts with a list of initial “update” messages, each looking like this:

```
A an vvvv mmmmmmmmm
```

or this:

```
S sn vvvv mmmmmmmmm
```

The second message type is only present for a socket interface. In that case, the whole list is additionally preceded by the standard header (node signature), which also includes the number of sensors, actuators, and their offsets (i.e., how many negatively-numbered sensors/actuators are present) – see Sections 6.1 and 6.4. This information is not written for a file (device) output.

The messages tell the current (initial) values of all defined actuators/sensors together with their ranges. The first number following the letter (A or S) is the decimal sensor/actuator index (between 0 and 255 inclusively), the next (hexadecimal) number is the value, and the last (also hexadecimal) number is the maximum. Note that the sensors/actuator numbers in the above messages are never negative. To transform them into the “logical” sensor indexes (as perceived by the praxis) you have to apply an offset assuming that sensor/actuator number zero in the output corresponds to the minimum sensor/actuator index as seen by the praxis.

All actuators appear before sensors, and both types of objects are listed in the increasing order of their numbers; thus, a hole directly reflects a sensor/actuator that is absent.

Following the initial update, subsequent updates are sent without the range component, i.e., the letter (A or S) is only followed by two numbers. The second number is always in hexadecimal and consists of exactly eight (hexadecimal) digits (no 0x prefix).

4.11 Storage modules: EEPROM, SD, information flash

VUE² allows you to model two kinds of external storage: generic EEPROM (which may also be used to mimic an SD card) and the so-called information flash (e.g., corresponding to the Flash Information Memory (FIM) available on MSP430 processors). Both types (i.e., EEPROM and information flash) can be present simultaneously. The list of operations applicable to them can be found in [11]. Operations on SD cards are mapped to the corresponding operations on EEPROM. Note that you cannot have them both at the same time (as at most one EEPROM module can be defined per node). There is no access to general code flash in VUE² (operations `cf_write`, `cf_erase`). These operations are void in VUE²: `ee_open`, `ee_close`, `ee_panic`, `sd_open`, `sd_close`, `sd_panic`, `sd_idle`, except that `ee_open` and `ee_close` (also `sd_open` and `sd_close`) keep track of power budget for the power tracker (see Section 4.13). Those of them that return values behave as if they always succeeded.



EEPROM is declared with the `<eeprom>` element (see page 12). The attributes of that element specify the parameters of the module, while the body may contain initializers (`<chunk>` elements) that preload values into specific fragments of the storage. Here is the list of attributes of `<eeprom>`:

size="n" or size="n,m" (where *n* and *m* are integer numbers)

This is the only one attribute that is mandatory, in the sense that its absence means that EEPROM is undefined. A possible application of such a declaration, e.g.,

`<eeprom></eeprom>`

is to indicate that the node should have no EEPROM even if there is one in `<defaults>`. Note that no partial inheritance from `<defaults>` takes place, i.e., if an EEPROM module is defined at a node at all, then all its parameters must be specified with that definition (the absent ones assume globally default values that need not match those in `<defaults>`).

The first number of size, *n*, specifies the total size of the storage in bytes. The second (optional) number, *m*, gives the number of pages (or blocks). This is important if you want to make sure that the erase operation applies to an entire number of pages/blocks, in which case *m* provides the requisite grain. If the number of pages, *m*, is present, then the total size *n* must divide evenly by *m* and the result (the page size) must be a power of two.

clean="xx"

The value is a single-byte hexadecimal number which specifies the contents of an erased byte. If the attribute is missing, the value defaults to FF.

erase="byte" or erase="page"

The attribute specifies the granularity of erase, i.e., whether you can erase individual bytes (this is the default) or pages. The latter case only makes a difference when the page size is specified (and it is larger than 1).

overwrite="yes" or overwrite="no"

The attribute indicates whether overwriting an already written byte (without a prior erase) produces the correct result (the first case, which also happens to be the default). In the second case, it is assumed that overwriting zero bits with ones has no effect.

timing="rl,ru,wl,wu,el,eu,sl,su"

This attribute specifies the timing parameters that determine the delays incurred by operations `ee_read`, `ee_write`, `ee_erase`, `ee_sync`. For those operations that admit a state argument (and can possibly block), i.e., all of the above except for `ee_read`, those parameters determine the amount of time elapsing until the respective operation unblocks after its start. This will translate into an actual delay modeled by VUE². For `ee_read` (which has no state argument and never blocks, VUE² cannot simulate the delay. This also happens when the state argument of `ee_write`, `ee_erase`, or `ee_sync` is `WNONE`. In that case, the delay is only applied to calculating the power usage by the power tracker (Section 4.13) and otherwise ignored. In particular, SD card operations (which do not accept the state argument) behave like the corresponding EEPROM operations with the state argument being `WNONE`.

The timing parameters are floating point numbers providing the lower and upper limits (in seconds) for the four operations (in the listed order) per one byte, except for `ee_sync` (which takes no length argument). The delay in each particular case is determined as a uniformly-distributed random number between the bounds. If not all numbers have been specified, the missing ones (from the end) are assumed to be zeros, which has the effect of not modeling any delays for the corresponding operation(s).

image="filename"



This attribute declares a file backup for the storage. If filename refers to an existing file, this file will be opened and its contents will appear as the initial image of the storage. If the file is larger than the formal size of the storage, it will be truncated down to size. If it is shorter (in particular, if its length is zero or it doesn't exist), it will be extended and filled up with "erased" bytes (depending on the clean attribute). Whenever some bytes are written to the EEPROM, those bytes will be stored in the file, which can be subsequently viewed and archived after the experiment.

It is not illegal to use the same filename for multiple nodes and may make perfect sense if the storage is used read-only. This is not checked, however, so you will mess things up if multiple nodes write to the same backup file. As a precaution, it is formally illegal to use this attribute for the <eeprom> element occurring in <defaults>.

EEPROM can be preinitialized with a sequence of <chunk> elements appearing within the body of the <eeprom> element (see page 12). One mandatory attribute of such an element is address providing the offset into the EEPROM where the specified chunk of bytes goes. The bytes themselves can be listed as the body of <chunk>. For example, this chunk:

```
<chunk address="8192">
    0 1 2 3 FE 0xAC 0 0 0 11
</chunk>
```

will preset 10 bytes starting at address 8192 with the specified contents. The numbers appearing within the body of a <chunk> are all in hexadecimal (the 0x prefix is optional) and each of them stands for exactly one byte.

Another possibility is to read the contents of a file into an EEPROM fragment, e.g.,

```
<chunk address="0" file="fonts.nok"></chunk>
```

In this case, the body of the <chunk> element is ignored, and the entire contents of the specified file are written into the storage at the specified address.

A single <eeprom> definition may include multiple chunks of different kinds. They can overlap (being applied in the order of their occurrence), but none of them is allowed to extend beyond the formal limits of the storage. An attempt to do that will be signaled as an error.

Note that initialization with chunks is compatible with backing files. For example, this definition is legal:

```
<eeprom size="536870912,1048576"
    image="myimage.bin" clean="00" overwrite="no">
    <chunk address="0">ba ca de ad</chunk>
    <chunk address="16384" file="picture.nok">
</eeprom>
```

and its outcome is intuitively clear. The contents of the initializing chunks (wherever they come from) will be written into the backing file.

Note that EEPROM (and information flash), unlike other node components, are not re-initialized after node reset.

Functionally, the information flash is a subset of EEPROM. The <iflash> element used for its definition accepts the same attributes as <eeprom> (with the same meaning), except for erase, overwrite, and timing. Even though clean is admissible, overwrite="no" is forced for <iflash>, as is erase="page". Similar to EEPROM, information flash can be initialized (the body of <iflash> may include <chunk> elements) and/or backed to a file.



4.12 Nokia LCD display N6100P

An `<lcdg>` element appearing as part of `<node>` (or `<defaults>`) equips the node with the model of a graphic LCD. The `type` attribute of this element determines the display model. At present, the only legitimate type is `n6100p`;²¹ thus,

```
<lcdg type="n6100p"></lcdg>
```

incorporates a virtual N6100P into the node. The body of the `<lcdg>` element should be empty. A sequence without the type attribute, i.e.,

```
<lcdg></lcdg>
```

indicates that the LCD model is absent and can be used to nullify locally a global declaration appearing in `<defaults>`.

4.13 Power tracker

The power tracker module allows you to maintain a record of energy usage by a node and, in particular, estimate the average amount of current drawn by the node within a certain time period. At present, the built in functionality of the power tracker covers: the CPU states (low power versus normal), the RF module, non-volatile storage (EEPROM, SD card), and sensors.

Power tracker parameters are specified on a per-node basis (see page 12) and may appear as part of a `<node>` element or in `<defaults>` (with the standard meaning). Here is a sample specification involving all four components that are traceable at present:

```
<ptracker>
  <output target="socket"/>
  <module id="cpu">0.3 0.0077</module>
  <module id="radio">0.0004 16.0 30.7 30.7</module>
  <module id="storage">
    0.030 0.030 10.0 15.0 17.0 16.0
  </module>
  <module id="sensors">0.0 2.5</module>
</ptracker>
```

The specification can include an `<input>` and/or an `<output>` element with the standard capabilities, e.g., as for SENSORS or PINS. Similar to SENSORS, an input command addressed to the module is an ASCII line. If the first character of such a line is T, then the line describes the timing of the command in the next line, similar to SENSORS or PINS. Otherwise, that character can only be C (and any remaining characters in the line are ignored). This command clears (i.e., zeroes) the tracker effectively starting a new measurement at the current moment.

The `<module>` elements describe (intentionally) the current usage of the respective components (modules) in their different states. The meaning of those states depends on the component. The first state (and the first number) has a standard meaning representing the default (reset) state of the module. For example, value 0.3 at the CPU `<module>` can be interpreted as 0.3mA drawn by the board's CPU in the default idle state assumed after reset. Note that the interpretation of all those numbers is up to the user, and they have no implied standard meaning.

The second value at the CPU `<module>` represents the power down state (7.7uA). This component uses only two values.

For the RF (radio) component (the second module), we have 4 numbers describing, respectively, the current drain in the off state, with the receiver on, with the transmitter on, and with both the receiver and the transmitter simultaneously on (if it makes a difference). Generally, if the expected sequence of values is longer than the one provided, all the

²¹ A document describing the API is available as part of the Seawolf project.



unspecified values are assumed to be the same as the last one. Thus, the last value for the radio <module> is redundant.

The storage module applies to EEPROM. The values respectively refer to the amount of current drawn by the module:

- in the off (or closed) state (e.g., after executing ee_close)
- in the on state (e.g., after ee_open) but otherwise idle
- while reading
- while writing
- while erasing
- while syncing

The amount of time needed for the module to remain in an active state (reading, writing, erasing, syncing) is determined from the timing parameters (page 39). If there are no timing parameters (for all or some operations), the corresponding current drain is not modeled (assumed to be zero).

For the sensors module, the second and possibly subsequent values refer to the current drained by the sensors or actuators (in the order of their numbers) while active. Note that sensors and actuators admit timing parameters (page 37). In the above example, the single "on" value (2.5mA) will apply to all sensors and actuators.

Not all modules have to be specified. A missing module uses no energy: its current drain is always zero regardless of the state.

If the output target of the power tracker is "device", i.e., the updates regarding current drain are sent to a file, VUE² will be writing to that file a message after every change in the state of any of the tracked components. Such a message looks like this:

U T [E] : A V

where T is the time of the state change in seconds (from the beginning of run), E is the elapsed time of the current measurement (counted from the last moment the tracker was zeroed), A is the accumulated average current drain from the beginning of the measurement (since E seconds ago), and V is the current drain at the moment (after the state change). All four numbers are floating point (the last two may include exponents).

If the output target is "socket", a line in the above format is sent to the remote agent at 1 second intervals for as long as the connection is on.

4.14 Pre-initialization

By pre-initialization we understand assigning initial values to some node attributes in a way that is conceptually different from the normal (dynamic or static) initialization in the node program. Intentionally, it corresponds to burning some characteristic values into the node's code flash memory, e.g., hard constants, that make the node unconditionally distinguishable from other nodes.

Pre-initialized values are represented in the input data as <preinit> elements, which can be sub-elements of <node> or <default>. Here is an example:

<preinit tag="SECRET" type="lword">0x8000ff01</preinit>

The mandatory tag attribute assigns a name to the preinit. The second (optional) type attribute determines the object type, which can be:

lword	a 32-bit long integer value (signed or unsigned)
word	a 16-bit integer value (signed or unsigned)
string	a character string

These indicators can be abbreviated down to the initial letter. If the type attribute is absent, it defaults to word.



The element's body contains the value, which should agree with the type specification. For types `lword` and `word`, the value should be a decimal number (possibly signed) or a hexadecimal value (beginning with `0x`). Regardless of its actual size, it will be truncated to the respective size of the object. For the string type, the body is simply viewed as a character string.

A preinit can be referenced in the praxis via this function:

```
IPointer preinit (const char *tag);
```

which returns the preinit value represented by the tag. The generic output type must be cast to the proper object type. This, however, only works for VUE². To make preinits transparent from the viewpoint of both views of the praxis, you can use the `PREINIT` macro, e.g.,

```
const lword SecretNumber =
    (lword) PREINIT (0xBACADEAD, "SECRET");
```

which accepts two arguments: the direct value to be used for the target system, and the symbolic preinit name to be used for VUE². When compiling for a real device, the macro will ignore the second argument and turn itself into a straightforward initializer for the variable. When compiling for VUE², it will ignore the first argument and become a call to `preinit`.

If the tag referenced by `preinit` is not found among the `<preinit>` elements associated with the current node, the function consults the preinits of `<defaults>`. If it is not found there, the function returns zero, i.e., the object is initialized to zero (or to a NULL string pointer). This corresponds to leaving the object uninitialized in the real world.

4.15 Mobility drivers

The underlying mechanisms present in SMURPH/SIDE [5] allow the programmer to create arbitrarily elaborate mobility models as external SMURPH processes. VUE² provides an interface to external agents that can modify coordinates of nodes by sending commands over sockets (Section 7.6). The same interface can be fed from files (or devices).

4.15.1 Declaring a mobility driver

A mobility driver accepting node positioning commands²² is not a node module (like UART, LEDS or PINS), because its domain is not restricted to a single node: it may affect the positions of multiple nodes essentially at the same time. One such driver, capable of receiving connections from remote agents over sockets, is available all the time and need not be declared in the input data file. We shall call it the *external* driver. It is also possible to declare *local* mobility drivers, which can modify node positions according to a local description, i.e., included directly in the input data or read from local files. Such a driver accepts a subset of the commands available to a remote agent connected to the external driver.

A local mobility driver is declared with the `<roamer>` element (see page 12), which is a sub-element of `<network>` and looks like this:

```
<roamer>
  <input source="..."> ... </input>
</roamer>
```

where the input source specification is essentially the same as for PINS (Section 4.8). A `<roamer>` element with `<input source="socket">` is ignored. Note that there is no `<output>` sub-element in `<roamer>`. While an external agent connected to a mobility driver over a socket can query the driver and receive feedback information (see Section 6.9), this functionality is not available to a local driver.

An arbitrary number of local mobility drivers can be declared in the same data file. Each of them can affect the position of an arbitrary number of nodes. Once a driver requests to re-

²² Strictly speaking, positioning commands apply to Transceivers rather than nodes.



position a node, any active positioning request regarding that node, possibly originating from another driver, is canceled and the new request takes over.

4.15.2 *Commands*

There are three types of commands accepted by a local mobility driver. These commands constitute a subset of requests available to external agents talking to a mobility driver over a socket. The simplest command assigns new coordinates to a given node and has this format:

M nn x y

where nn is a node number (according to the numeration of <node> elements), and x and y are the new planar coordinates. The operation amounts to teleporting the node to the new location. The move is instantaneous. Note that the coordinates cannot be negative.

Similar to PINS (page 34), it is possible to delay the interpretation of subsequent requests with a T command, e.g.,

T +0.01

will cause a 10 ms delay before interpreting the next request, while

T 3600

will halt the input until the model has been run for one hour since its startup.

With a sequence of appropriately timed (tiny) teleportations one can implement any movement, closely approaching smooth navigation along any curve at any (possibly variable) speed. It is tedious, however, to procure such data sets by hand. To simplify typical experiments, the mobility driver offers a standard random-way-point roaming model, which is invoked with the following command:

R nn x0 y0 x1 y1 smin smax pmin pmax duration

where all numbers except nn (the node number) are floating point. When such a request is accepted, the indicated node starts roaming and continues doing so for duration seconds according to the pattern prescribed by the remaining parameters. If duration is zero or negative, the roaming continues forever, or rather, until another repositioning request is issued to the node. In the meantime, the driver is free to process other commands (the roaming is carried out in the background).

The first four floating point numbers, i.e., x0, y0, x1, y1, describe the rectangle bounding the node's roaming area. Note that x0 must not be greater than x1, and y0 must not be greater than y1. Besides, all coordinates must not be negative. The node will travel according to this algorithm:

1. A uniformly distributed random target location is generated within the bounding rectangle as well as a uniformly distributed random speed between the specified minimum (smin) and maximum (smax) in meters per second. The node moves at this speed towards the target location.
2. Upon reaching the target location, a uniformly distributed random pause time is generated between pmin and pmax seconds. The node rests for this much time and proceeds from 1.

This process continues for duration seconds, or indefinitely (if duration is zero or negative). It will be interrupted when the same or a different mobility driver issues any re-positioning command to the node.

Taking advantage of the string source for the ROAMER, you can easily set up multiple random-way-point mobility scenarios for multiple nodes. For illustration, consider this declaration:

<roamer>



```

<input source="string">
  R 0 [0.0 200.0 0.0 200.0] [3.5 10.0] [1.0 10.0] -1
  R 1 [0.0 200.0 0.0 200.0] [3.5 10.0] [1.0 10.0] -1
  T 1800.0
  R 5 [0.0 200.0 0.0 200.0] [3.5 10.0] [1.0 10.0] -1
  R 7 [0.0 200.0 0.0 200.0] [3.5 10.0] [1.0 10.0] 7200.0
  T +1800.0
  M 5 40.0 50.0
</input>
</roamer>

```

Nodes 0 and 1 start roaming immediately at the beginning of the experiment. After 30 minutes, nodes 5 and 7 join them. Node 5 stops roaming after another 30 minutes when it is teleported to location (40.0, 50.0) and becomes stationary. Node 7 keeps moving for two hours before stopping (at some random location), while nodes 0 and 1 roam forever.

The above example suggests that the command syntax allows for non-numerical characters to be interspersed among the numbers (we used square braces for clarity). This only applies before floating point numbers and should be viewed as an undocumented feature that may be removed without warning. The maximum length of a single request line is 112 characters.

Note that a node whose location has been declared non-movable (see page 24) cannot be moved. An attempt (by a mobility driver) to move it will trigger an error.

4.16 Panels

By default, the program (praxis) running at a node is automatically started as soon as the input data file is read and processed, at the very beginning of the model's execution. It is possible to have some nodes stopped initially by specifying `start="off"` in their `<node>` elements (see page 12). You may even have all nodes stopped initially (by putting `start="off"` as an attribute of `<defaults>`) and then start them later, e.g., at specific moments. Once started and running, a node can be stopped, started, and reset an arbitrary number of times. This process can be described in the input data (or a separate file); it can also be controlled by external agents.

4.16.1 Declaring panels

The respective data element, called `<panel>`, is illustrated in the sample data set on page 12. Its full format is similar to that of `<roamer>` (Section 4.15) and looks like this:

```

<panel>
  <input source="..."> ... </input>
</panel>

```

where the input source specification is essentially the same as for PINS (Section 4.8). A `<panel>` element with `<input source="socket">` is ignored. Similar to `<roamer>`, there is no `<output>` sub-element in `<panel>`. While an external agent connected to a panel driver over a socket can control the status of nodes and receive feedback information (see Section 6.10), this functionality is not available to a local driver. An arbitrary number of `<panel>` elements can be present in the same data file. Each of them can affect the status of arbitrary nodes. For example, a node stopped by one panel can be restarted by another. Stopping a stopped node or starting a running node has no effect. Resetting a node always starts it up, regardless of whether it was stopped or running before the reset.

4.16.2 Commands

The simple set of commands understood by a panel consists of the timing request `T` – as for PINS (page 34) and three status change requests (in all cases, `nn` is the node number):

<code>O nn</code>	- to switch the node on
<code>F nn</code>	- to switch the node off
<code>R nn</code>	- to reset the node



For illustration consider the following sequence:

```
T 30.0
O 1
T +5.0
O 2
T +10.0
F 1
F 2
R 3
```

Thirty seconds after the beginning of execution, node 1 will be switched on, then 5 seconds later, node 2 will be switched on, and after 10 more seconds, nodes 1 and 2 will be switched off and node 3 will be reset.

4.17 Structuring the data set

The XML data parser of SMURPH [5] makes it possible to build the data set of (possibly recursively) “included” pieces. Any element looking like this:

```
<xi:include href="filename"/>
```

is logically replaced in the data set with the contents of the file named by the href attribute. The included file may include other similar tags, and so on. The xi: prefix can be skipped, so all the following variants are equivalent:

```
<xi:include href="collector_node.xml"/>
<xi:include href="collector_node.xml"></xi:include>
<include href="collector_node.xml"/>
<include href="collector_node.xml">Extra data</include>
```

The body of the last element is ignored (treated as a comment).

When the package is installed the standard way [2], directory DataLib in PICOS/Apps is declared as the include library for XML data files. This means that if the file name specified in the href attribute of an <include> element does not start with / (i.e., the path is not absolute), and it cannot be found in the current directory (i.e., the one the simulator has been invoked in), then it is searched in PICOS/Apps/DataLib. Thus, that directory is intended as a storage for data snippets of global interest, e.g., channel definitions, standard node layouts, and so on. Regarding node layouts, one more natural way to store them is with the board definitions (see Section 4.4.6).

4.18 Agent “visualization” data: the concept

The input data set may include other items, not described in Section 4, which are not interpreted by the simulator as such, but can be passed to agents for their specific use. The simple idea is that any elements of that data set that are not recognized by the simulator are ignored by the program.²³ One of the possible requests that may arrive from an agent is XMLDATA (see Section 6), i.e., a query for the simulation data set. In response to such a query, the program will send to the agent the complete data set, with all the possible “inclusions” (Section 4.17) resolved. Then the agent will be able to parse the set by itself selecting the parts that it finds interesting.

At present, the only serious agent connecting to the simulator is udaemon (Section 7); although the terminal emulator, piter, is also able to take advantage of a direct agent connection to access a virtual UART [8]. Unlike piter, whose role is simple and confined to visualizing a (virtual) UART in a single and straightforward terminal window, udaemon can often use a few hints describing the visualization layout of the various model components. Those hints (described in detail in Section 7.11) are inserted as various (additional) elements into the model's data file.

²³ For one thing, this makes it possible to insert creative comments into the data set.



It so happens that one of those “additional” elements in the data set that formally falls under the jurisdiction of `udaemon` has to be subjected to some interpretation by the simulator as well. That element specifies the parameters of the ROAMER window (Section 7.11.3) which may include the whereabouts of the file containing the background image to be displayed in the window. As the location of that file can only be known to the simulator (note that the agent may be executed on a different machine), the program must be prepared to send it to the agent upon request. Thus, it has to interpret the respective element in the data set, decode the file name, and stash it for the occasion. Note that the idea of a background image (to visualize the network against) is pretty general and likely to be useful to many agents. Thus, we may assume that the data item conveying this information (see Section 7.11.3) is of more general relevance.

5 Simulator call parameters

In those rare cases when you have to invoke the simulator manually (instead of letting PIP do its job), this section comments on the few program call parameters that may be of relevance.

Section 19.3 of the SIDE document [5] describes all the generic call arguments applicable to any SIDE simulator. Not all of them make sense in our context, and you probably shouldn't care too much about them. Here is the most natural way to invoke of the simulator:

```
side data_set.xml
```

The single argument is interpreted as the path to the input data file. The simulator will write to standard output. The output will contain the simulator's understanding of the parsed input data set (in a more or less self-explanatory form) plus any trace lines, mostly caused by diag statements in the praxis.

The output can be directed to a file, e.g.,

```
side data_set.xml output.txt
```

One special case of the output file name is the `+` sign, e.g.,

```
side data_set.xml +
```

which has the effect of using standard error instead of standard output. The two file names, with the output file name being optional, belong to the standard set of arguments of any SIDE simulator. Some optional VUE²-specific arguments (which are not explained in the SIDE manual) can be specified following `--` (which terminates the standard argument list), e.g.:

```
side data_set.xml -- -s 2.0
```

Here is the complete list of those arguments:

-s *n*

The argument *n* is a floating point number specifying the slow motion factor, i.e., how much to slow down the modeled flow of time with respect to real time. For example, if *n* is 2, then every second of virtual time will be spread over two seconds in real time. Note that *n* can be less than 1. If *n* is zero, the model will execute at the full speed of the CPU, in pure event-driven simulation mode, without trying to match the virtual time to real time.

-r *n*

The argument *n* is an integer number between 0 and 1000 inclusively. It specifies the so-called resync interval in milliseconds, which is the granularity at which the simulator synchronizes events to real time. If the slow motion factor is zero (the model runs in event-driven mode), the resync interval is ignored.

-n *label node_data_path*



-n *node_data_path*

The argument, which can occur multiple times, specifies a supplementary data file (see Section 4.4.6) to be interpreted as a board-specific node layout for the program identified by the *label*. The second case, with the label absent, applies to a single-program praxis.

-p *agent_port*

The argument specifies a non-standard port for agent connections (Section 6). The argument can be a number between 1 and 65535. The default port is 4443. When this argument is present, any port specification in the data set (in the <network> element – Sections 4, 6) is ignored.

6 The agent protocol

A running VUE² model makes a socket available for connections from agents. Such agents may implement GUI to various module components (UART, LEDS, PINS, ROAMER, etc.) or provide an interface to OSS programs for the target praxis (executed on a real network). For example, an agent may implement an open ended UART driver (like a COM port under Windows) connected to a node running under VUE².

The standard port number of the socket opened by a VUE² model is 4443. It can be changed via the port attribute of <network> (see Section 4), e.g.,

```
<network nodes="48" port="5590">
```

or with a program call argument (see Section 5), which can be useful, e.g., if multiple VUE² models are run on the same system.

At present, VUE² implements these functions (i.e., connection types) for agents:

UART	for connecting to a node's UART
LEDS	for connecting to a node's LEDs module
EMUL	for connecting to a node's EMUL module
PINS	for connecting to a node's pins module
CLOCK	for reading the virtual clock of the model
ROAMER	to affect/retrieve the locations of nodes (and more)
PANEL	to control the on/off status of nodes
SENSORS	to receive values from virtual sensors and affect virtual actuators
LCDG	to send data to the virtual graphic LCD
PTRACKER	to receive updates regarding energy consumption by nodes
XMLDATA	to receive the XML data file of the experiment
STOP	to enable agent programs to terminate the model

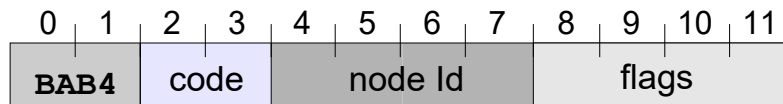


Figure 3: Connection request sequence.

Except for CLOCK, ROAMER, and PANEL, there can be multiple active instances of any connection type at any given moment – typically referring to the respective components of different nodes. For example, several UARTs belonging to different nodes can be interfaced to agents simultaneously.

With the single exception of XMLDATA, the interface is session-oriented, meaning that an agent does not connect to the model for a single inquiry, but sets up a session during which it will be involved in an exchange of potentially unlimited length. The connection can be



broken by the agent at any time by simply disconnecting, but (normally, i.e., no error) it is the client who decides to end the connection.

An XMLDATA request is special in the sense that an agent issuing this request only asks the simulator for the contents of the input data file (Section 4.18). Having sent the file, the simulator will close the connection. This is unlike any “normal” session which remains on until the agent requests its termination. Also, even though the request is unrelated to any particular node, the simulator will admit multiple (parallel) XMLDATA requests (arriving from different agents).

6.1 The handshake

A connection is initiated by the agent (client) connecting to the agent port of the VUE² model for a TCP (stream) session. Immediately after receiving a connection, the agent should send a polling sequence shown in Figure 3. It consists of 12 bytes interpreted as two short numbers and two long numbers in the network format, i.e., MSB first. The first number is a magic sequence used for a quick assessment of the request's sanity. The second short number, code, describes the requested service type. The next four bytes amount to an integer number generally interpreted as a node identifier – for those requests that relate to specific nodes. The final four bytes comprise another integer number interpreted as flags which may affect the interpretation of some requests. Only two flags (bits 0 and 1) are used at present.

The node identifier can be interpreted either as the serial (SMURPH) number of the node or as the node's local host ID (Section 4.4), i.e., the lower half of the host ID attribute (also known as the node's network ID). This is determined by bit number zero in flags: if that bit is set, the node identifier is interpreted as the local host ID.

Having received a polling sequence, the VUE² program responds with four bytes (a 32-bit unsigned number in network format) interpreted as an acknowledgment (Figure 4). The least significant byte of that number indicates a success or failure. If its value is 129 (decimal), it means that the request has been accepted. The upper three bytes may return additional information (value) to the connecting program. For example, the UART module passes in that value the UART's bit rate as the number of bits per second divided by 100.



Figure 4: Acknowledgment format.

If the acknowledgment code is different from 129, it means an error. Having sent the error code, the VUE² program immediately closes its end of the connection. Here is the list of possible error values:

- 0 wrong magic sequence
- 1 node number out of range
- 2 illegal (unimplemented) request code
- 3 some agent is already connected to this particular module
- 4 timeout; this code is sent if a complete 8-byte polling sequence does not arrive within 30 seconds from the moment of connection
- 5 the module (UART, PINS, LEDS, ...) is present at the node, but it has no socket interface



- 6 this code is sent when the program discovers that the other side has closed the connection, before closing its end; thus, it is unlikely to be ever received
- 7 the request sequence is too long
- 8 illegal request or query
- 9 ambiguous node identifier (when the identifier is interpreted as host ID)²⁴
- 128 the node has no such module

Specific connection types may require additional (module-specific) handshake components before commencing the proper session. For all connections to modules associated with specific nodes (i.e., all connection types except for CLOCK, ROAMER, PANEL, XMLDATA, and STOP, the acknowledgment word (see Figure 4) is immediately followed by the so-called node signature, which is an ASCII line looking like this:

P nn ps hh tt <typename>: ...

The line starts with the letter P followed by the SMURPH node number, the power (up/down) status of the node, the host ID (see Section 4.4), the total number of nodes in the network, and the type name of the node. Items nn, hh, and tt are unsigned integer numbers. The power status is a single letter: O for on and F for off. The fifth item is the SMURPH type identifier of the node (enclosed in < ... >), which is the SMURPH name of the class representing the node, also being a slightly mangled derivative of the “program’s label” (especially relevant and valuable for those praxes that consist of multiple programs [7]).

The way to transform the SMURPH type identifier of a node into the program’s label is to remove and initial sequence encapsulated between underscore characters. Here is the regular expression matching the part to be removed:

^_+[^_]+_*

The signature is terminated by a colon. Depending on the connection type, that colon may (but doesn’t have to) be followed by other (module-specific) parameters. The line terminates with a single newline character.

In most cases, the agent protocol for a module is a simple extension of the sequences described in the corresponding subsection of Section 4. The presence of a node signature in the output (at the very beginning of the exchange) is often the most important discriminating factor of an agent session (carried over a socket), in comparison to the “device” interface of the module.

When a node is in power down state, its modules are dormant (and generate no output that would arrive from the program to the agent). The general rule regarding input from the agent is that the input is absorbed by the program (so it doesn’t linger inside the socket) and ignored. One exception is timed input (e.g., see Section 4.5.1) which is governed by a schedule. Note that the agent can learn when a node is powered down (Section 6.10) and block the input at the source (if so desired). Also note that for a non-socket interface to a module, the input is blocked while the node is powered down, such that no input is ever lost. This also concerns timed input that becomes “obsolete” while the node is powered down. Such input will be presented to the module as soon as it gets powered up.

6.2 UART protocol (request code 1)

This kind of request requires a valid node identifier passed in the polling sequence (Figure 3). If the node identifier is OK, and the indicated node is equipped with a UART module with socket interface, and no other agent is connected to that UART at the time, the request is accepted. Then, the simulator sends an acknowledgment word whose value field (Figure 4) contains the UART rate expressed in hundreds (i.e., divided by 100) followed by a generic node signature (no additional parameters). From that point on, the connection becomes

²⁴ Note that formally host ID’s (even more so local host ID’s) need not be unique. The error occurs when the specified local host ID maps to more than one node.



entirely dedicated to the UART. This means that whatever the agent sends over the socket will appear as input on the UART, and whatever the praxis writes to the UART will be sent to the agent over the socket. This will continue until the session is torn down (closed) by the agent (or until the VUE² program terminates).

The format of the data sent/received by the UART conforms to the coding and type attributes associated with the UART in the input data set (Section 4.5). In particular, if the input is “timed”, the data must be organized into packages preceded by the playback time. Normally, this kind of operation is not very useful for a socket connection, but it is available. Note that when the playback time is in the future, the input will be blocked until that time. Similarly, with “hex” encoding of the respective end, the data follows the hexadecimal format described in Section 4.5.

6.3 PINS protocol (request code 2)

This request must provide a valid node identifier. If the identifier is OK, and the indicated node is equipped with a PINS module with socket interface, and no other agent is currently connected to the module, then the request is accepted. Following the acknowledgment word (whose value field is zero), the VUE² program sends a node signature with four additional numbers following the colon:

`... : np na d0 d1`

where np is the total number of pins, na is the number of ADC-capable pins (note that they constitute an initial subset of all pins), d0 is the number of the first DAC-capable pin, and d1 is the number of the second DAC-capable pin. If there are no DAC-capable pins, both d0 and d1 are -1.

Then, unprompted, the program follows the signature by the full list of updates reflecting the current status of all pins. Each such a message takes a complete ASCII line of text, as described in Section 4.8, terminated with a single newline character. The agent may assume that the messages arrive in the order of pin numbers from zero up.

No other message types ever arrive from the VUE² end. Whenever the status of a pin is changed by the praxis, a pertinent message is queued for transmission. Such a message always refers to a single pin.

The agent is able to affect the status of pins by sending messages over its end of the socket that look exactly like those described in Section 4.8. Such a message should be an ASCII string ending with a single newline character. With an online agent connection (as opposed to reading the pin status from a file), there is little demand on T requests, although they are not prohibited. Note that if such a message specifies a moment in the future, the input will be blocked until that time.

6.4 SENSORS protocol (request code 7)

This request must provide a valid node identifier. If the identifier is OK, and the indicated node is equipped with a SENSORS module with socket interface, and no other agent is currently connected to the module, then the request is accepted. Following the acknowledgment word (with zero value field), the VUE² program sends a standard signature (page 50) with four additional parameters:

`... : an oa sn os`

which are: the number of actuators (an), the offset of actuator number zero (oa), the number of sensors (sn), and the offset of sensor number zero (os), as defined by the node. Accounting for the possible holes (Section 4.10), an/sn is the maximum number of defined actuators/sensors. The respective offsets tell the absolute value of the minimum negative number of an actuator/sensor, or zero if there are no negatively numbered actuators/sensors. For example, if sensor number -1 is the only negatively numbered sensor, os will be equal 1.



The signature is followed by the full list of updates reflecting the current values and ranges of all actuators and sensors. Each such a message takes a complete ASCII line of text, as described in Section 4.10, terminated with a single newline character.

Then the only message types subsequently arriving from the VUE² end are S and E (see Section 4.10). Whenever the value of a sensor/actuator is changed by the agent (in the first case) or by the praxis (in the second), a pertinent message is queued for transmission. Such a message always refers to a single sensor/actuator. Note that only the initial updates carry information about the ranges (Section 4.10).

The agent is able to affect the values of sensors (not actuators) by sending messages over its end of the socket that look exactly like those described in Section 4.10. Such a message should be an ASCII string ending with a single newline character.

6.5 **LEDS protocol (request code 3)**

This kind of connection works one way, i.e., following the initial 12-byte polling sequence (including a valid node identifier), the agent never sends anything to the VUE² program. Immediately after the acknowledgment word (with zero value field), the VUE² program sends to the agent a standard signature (page 50) including the initial configuration of LEDs:

```
... : F LLLLL ... LLL
```

where the part following the colon corresponds to the arguments of the U message from Section 4.6. Following the handshake, a U message will be sent whenever the status of a LED changes.

Additionally, to be able to detect the agent's disappearance, the simulator sends a dummy NOP message, which is simply a single newline character, every 10 seconds, unless there is a LED status change to report. Note that no NOP messages are written when the LEDS module is interfaced to a file.

6.6 **EMUL protocol (request code 10)**

Similar to LEDS, the connection is only in the output direction, i.e., following the initial 12-byte polling sequence (specifying a valid node identifier) the agent never sends anything back to the VUE² program. Following the acknowledgment word (with zero value field) + the standard vanilla signature (no additional parameters), the program will be sending to the agent emul messages (encoded as explained on page 33) separated by newline characters.

To be able to detect the agent's disappearance, the program will be sending a dummy NOP message, which is simply a single newline character, every 10 seconds, unless an emul message materializes in the meantime. Note that no NOP messages are sent when the module is interfaced to a file.

6.7 **XMLDATA protocol (request code 11)**

This is a simple request for the input data set of the simulator. Having received the initial 12-byte request sequence (whose node ID field is ignored), the program responds with the standard acknowledgment code whose value field contains the length of the data set in bytes. This is immediately followed by that many bytes comprising the actual set after which the program closes the connection.

Supplementary data with board-specific node layouts (see Sections 4.4.6 and 5) is simply appended to the regular data and encapsulated into a <supplement> element. Then, every node layout is additionally encapsulated into <board> which specifies the program label as an attribute, e.g.,

```
<supplement>
  <board type="col">
    <node> ... </node>
  </board>
</board type="tag">
```



```

        <node> ... </node>
    </board>
    ...
</supplement>

```

This way, the recipient perceives all sets as a single XML file with two elements at the root level: <network> and (optionally) <supplement>.

The data set arrives in ASCII and looks exactly as the original input data file with all the <include> elements (Section 4.17) resolved, i.e., the data set is complete. Note that the maximum number of characters in the set (the maximum size) is 16M.

6.8 STOP protocol (request code 12)

The purpose of this simple protocol is to make it possible for an agent to terminate the execution of a VUE² model. Having received the request (the node ID field is ignored), the program responds with the standard acknowledgment, opens a socket to the agent, and listens on the socket. Any data arriving on the socket is ignored, but when the socket is closed by the agent, the model will terminate. That is accomplished by issuing a *terminate* request to *Kernel*, which is the standard SMURPH incantation to (normally and gracefully) request termination from within the model program [5].

Note that by waiting for the closure of the agent socket the program will also terminate when the agent exits inadvertently, e.g., having been killed by the user.

6.9 ROAMER protocol (request code 4)

By following this protocol, the agent is able to carry out the operations described in Section 4.15.2, as well as receive feedback from VUE² regarding node positions, the combined status of their LEDs, output pins, and the so-called highlight attributes (Section 7.11.6). Only one remote ROAMER connection can be active at any time.

Having received the request, the program ignores the node ID field and looks at bit number 1 (the second bit from the right) in flags (Figure 3). If that bit is set, the program checks if the input data file included the location of a background image file (Sections 4.18, 7.11.3) and if the file can be opened. If that is the case, the program sends the file to the agent. The value field of the acknowledgment sequence (Figure 4) contains the length of the file (in bytes), and the acknowledgment sequence is immediately followed by that many bytes of the raw file content. Note that this sets the limit of 16MB for the file length.

If bit 1 in flags is cleared, or if the input data set did not specify the background file location, or if the file cannot be opened by the simulator, the acknowledgment sequence contains a zero value field (and nothing is sent to the agent).

The rest of the session exchange is in ASCII, with lines terminated by (single) newline characters. The VUE² program expects requests from the agent. The agent may query the program for the position of a given node with a command that consists of the letter Q followed by a single nonnegative (SMURPH) node number, e.g.,

Q 49

In response, the program will send a line looking like this:

P nn ps hh tt <typename>: x y mo <leds,pins> [vcolor,vnote]

The part up to (and including) the colon is a standard signature (page 50) of the node to which the query has been addressed. The remaining items amount to two floating point numbers (x, y), one Boolean value (mo) which can be 0 or 1, and four strings (leds, pins, vcolor, vnote) encapsulated in special brackets to make the line easier to parse. This is because the strings are independently optional (any of them can be absent), e.g.,

P 13 0 225 21 <__NT_Collector>: 12.467 77.921 1 <0121,> [,]



is a legitimate line. Note that, although the strings in brackets are optional, the brackets, as well as the commas, are not.

The two floating point numbers are the node coordinates in meters. The Boolean flag that follows them indicates whether the node is movable (1) or not (0) – see page 24).

Both *leds* and *pins* are sequences of digits describing the output status of the node's LEDs and pins, respectively. A given string is only present, if the node is equipped with the corresponding LEDS/PINS module – Sections 4.6 and 4.8. One role of such a string is to enable pin/LED-driven node coloring (see page 70). For the *leds* string, the first character tells the currently effective blink rate (0 – slow, 1 – fast) and the remaining characters provide the LED status (0 – off, 1 – on, 2 – blinking). For example,

12011

means that the fast blinking rate is in effect, LED number 0 is blinking, LED number 1 is off, and LEDs 2 and 3 are both (steady) on. For the *pins* string, character number *k* (counting from zero) corresponds to pin number *k* and is 1 if and only if pin *k* is currently defined as digital output and its status is high, and 0 otherwise (0 and 1 are the only legitimate values).

The role of the highlight attributes *vcolor* and *vnote* is to tell the agent to (temporarily) highlight the node, e.g., marking the fact that it has reached some interesting state. If the *vcolor* string is present (nonempty), then it encodes an integer number to be interpreted by the agent as a color temporarily overriding the node's coloring scheme (see Section 7.11.4). Within *udaemon* (Section 7) a small initial range of *vcolor* values can be preset to index a list of some standard predefined colors, with larger values interpreted directly as 3-byte RGB encodings. The other highlight attribute, *vnote*, is a piece of text to be shown (flashed) at the node, usually (but not necessarily) together with the color highlight. The details are described in Section 7.11.6.

If the agent knows nothing about the network (as in connecting for the first time), it can always safely issue a query for node 0. Then, having learned (from the signature) the total number of nodes, it can poll them individually, e.g., in sequence. Also note that the agent may consult the input data file of the simulator (acquired via an XMLDATA request – Section 6.7) to learn about the network configuration.

The agent may the commands described in Section 4.15.2. Also, it will receive an update whenever 1) the position of a node changes, including changes incurred by the agent itself, or 2) the value of a LED or an output pin at a node changes, including a change in the LED blink rate, or 3) the configuration of highlight attributes for the node changes. In other words, an update is triggered whenever there is a change in any of the (mutable) attributes belonging to the set shown in a P-message.

Note that local mobility drivers may be changing things behind the scenes. VUE² tries to reduce the number of unnecessarily updates to avoid overflowing the connection with traffic under heavy mobility scenarios.

A move (M) or roam (R) message (see Section 4.15.2) issued from an agent to a non-movable node is treated as an error (non-fatal to the simulator) which results in error code 8 (illegal request or query) sent in response and an immediate disconnection of the agent. Note that the agent can easily know which nodes are non-movable, so it can refrain from trying to move them.

An update message begins with the letter U and looks like an abbreviated P-message :

U nn ps x y <leds,pins> [vcolor,vlabel]

where the values are exactly as for a P-message.

Note that node coordinates cannot be negative. Having received an invalid request, i.e., one specifying an illegal node number or a negative coordinate, the program sends error code 8 to the agent and closes the connection.



6.10 **PANEL protocol (request code 5)**

Similar to ROAMER, this type of connection requires no node identifier (the field is ignored in the polling sequence). By following this protocol, the agent is able to carry out the operations described in Section 4.16.2, as well as receive feedback regarding the on/off node status. Only one remote PANEL connection can be active at any time. Following the acknowledgment word sent by the VUE² program to the agent (whose value field is zero), the rest of the conversation is in ASCII, with lines terminated by (single) newline characters.

If bit number 1 (second significant bit) in flags (Section 6.1) is set, then, immediately following the acknowledgment, the VUE² program sends to the agent the complete list of On/Off states of all nodes in a single line with this format:

nn:xxxxx...xxxxx

where nn is the total number of nodes and the string following the colon consists of letter O and F representing the status of individual nodes (O – on, F – off). The number of characters in the string is exactly equal nn.

If bit number 1 is not set in flags, then the above information is not sent. In such a case, the agent can poll the program for status of individual nodes. In addition to the commands described in Section 4.16.2, one more (query) request is available to the remote agent, which looks like this:

Q nn

where nn is a SMURPH node number. If nn is a legitimate node number, the program sends in response a line in the following format:

signature s

where signature is the signature of the queried node (terminating with a colon – see page 50) and s is a single character: O (the node is on) or F (the node is off).

In addition to being able to issue the commands described in Section 4.16.2, the agent will also receive an update whenever the status of a node changes (e.g., due to the action of a panel described in the input data set – see Section 4.16), including changes incurred by the agent itself. Such an update message is a line looking like this:

nn s

where nn is the node number and s is its new status (O/F). Note that when an active node is reset, the agent will receive a single message reaffirming the node's previous (on) state. The agent can tell that the node has been reset when it receives a status update of O when the last-reported status of the node was also O.

Having received an invalid request/query, i.e., one specifying an illegal node number, the program sends error code 12 to the agent (a single byte) and closes the connection.

6.11 **CLOCK protocol (request code 6)**

With this simple protocol, the agent can receive time information from the VUE² program. The node ID field of a CLOCK request sequence is ignored. Following the acknowledgment word (whose value field is zero), the program will be sending to the agent at second intervals the number of virtual seconds from the beginning of execution. This number arrives as a four-byte binary integer in the network format. Every message consists of exactly four bytes.

Multiple simultaneous connections to this service are OK.

6.12 **LCDG protocol (request code 8)**

This is a one-way protocol with data being sent solely to the display. The request parameter should specify a valid node identifier. Following the acknowledgment word (with zero value field) + the standard node signature (no extra parameters), the program will be sending to



the agent display updates consisting of binary short (16-bit) words in the network format. The most significant 4-bit nibble of a word determines the type of information carried in it:

- 0 means that the remaining 12 bits of the word contain the value of a pixel (4 bits per pixel: RGB, from most to least significant); the pixel is to be stored in the "current" position on the screen (as explained below)
- 1 means that remaining 12 bits of the word contain a command (as explained below)
- 8--15 i.e., the most significant bit being set, means that the word contains a repeat count for the last pixel; whatever last pixel value was received from the emulator, it must be repeated $(w \& 0x7FFF) + 1$ times (in addition to the original first appearance), where w is the word content

Here are the command codes:

- 0x300 (i.e., $w = 0x1300$); four words following this one contain the bounding rectangle of an area to be updated (filled) with subsequently arriving pixels; the rectangle is specified as the ending value of X, the starting value of Y, and the ending value of Y (the coordinate of the left upper corner of the display is 0, 0)
- 0x400 end of update; this command means that a logically complete series of updates has been concluded and, for example, it now makes sense to present a new updated variant of the display to the user
- 0x100 switch the display on
- 0x200 switch the display off

In addition to defining a bounding rectangle, command 0x300 resets the current pixel position to the left upper corner of the rectangle, i.e., the starting X and Y coordinates. Whenever a new pixel (including auto replications) is stored, the X coordinate is advanced until it exceeds the ending coordinate, in which case it wraps back to the starting X coordinate, while the Y coordinate is incremented by 1. When the Y coordinate exceeds its ending value, it wraps back to the starting value, and so on.

6.13 PTRACKER protocol (request code 9)

Following the standard handshake, including a valid node identifier, to which the simulator responds with a vanilla signature of the node, the agent will be receiving from the simulator a message, as described in Section 4.13, every second or whenever the state of one of the monitored components changes, whichever comes first. This is an ASCII line terminated with a single newline character. When the agent wants to zero the tracker (i.e., start the measurement from scratch), it should send back a simple command consisting of the letter C followed by a newline.

7 UDAEMON

Here we describe the functionality of *udaemon*, which is a Tcl/Tk program implementing a GUI agent for conversing with a VUE² model in execution. The program accepts four optional call arguments:

- A port number (in decimal) used by the VUE² program. By default, this number is 4443 and agrees with the VUE² default (Section 6).
- -R
- -T
- -P [file name]



When started, the program opens a window that looks as shown in Figure 5. This window is the launcher of a number of different interfaces, corresponding to the protocols described in Section 6. The area below the buttons displays various textual messages (the log), which, in particular may include error messages. The area is scrollable and stores the last 1024 lines of the log (which practically always means everything).

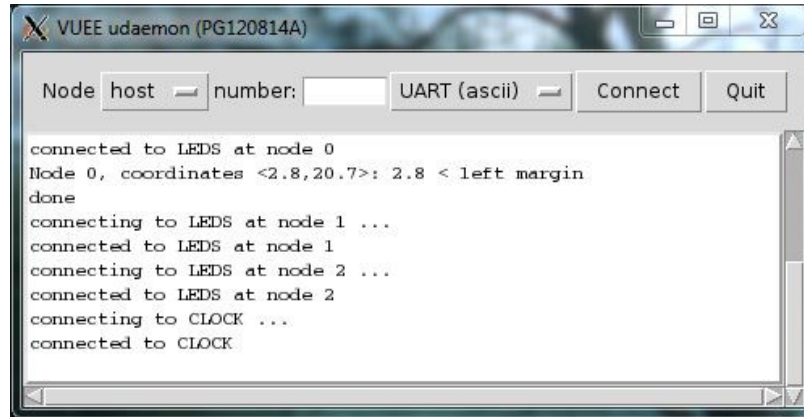


Figure 5: The root window of udaemon.

The text area labeled “Node [host] number” is used to insert the SMURPH node identifier for those interfaces that require one. The “host” part of the entry label can be flipped to “serial” thus changing the interpretation of the node identifier (see Sections 4.4 and 6.1). The selection button, initially showing “UART (ascii),” offers the menu presented in Figure 6. Having selected a given interface (and, if required, inserted a node identifier in the text area), you can click the Connect button to bring up the respective interface window. A generally more convenient way of requesting node-related interfaces is offered by the ROAMER window (see Section 7.6).

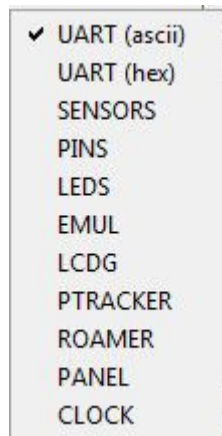


Figure 6: The selection menu of udaemon's root window.

The -R option inverts the interpretation of the y-coordinate in the ROAMER window (Section 7.6). By default, the coordinate grows from bottom to top (with zero at the bottom); -R changes that to zero at the top and growing down.

With -T, the program will issue a STOP request to the agent immediately upon connection (Section 6.8). This way, when udaemon quits, the model will terminate as well.



Using -P, you can specify a plugin file providing functions for converting/visualizing UART data arriving from the nodes as well as the user input to the UART terminal (see Section 7.1.2 for details). If -P is present but not followed by any file, the default plugin file `uplug.tcl` is assumed. If `uplug.tcl` is absent, but a file named `shared_plug.tcl` is present, then that file is assumed.²⁵

When started, `udaemon` immediately tries to issue an XMLDATA request (Section 6.7) to the simulator to acquire the simulator's data set for the purpose of extracting from it visualization data (Section 7.11). If the connection fails at this stage (i.e., the simulator is not running already), `udaemon` gives up (it means that it will not be using any model-specific visualization data), but does not quit.

Note that if you want to make sure that `udaemon` has been supplied with the visualization data from the input data set, and the data set is only available from the simulator, then the simulator must be started before `udaemon`. This is because `udaemon` tries to fetch the data only once (upon startup).²⁶

7.1 The UART interface

Note that the UART interface occurs in two versions: “ascii” and “hex.” If a UART plugin is present (see Section 7.1.2), a third UART variant, “plug”, becomes available. The “plug” version leaves it up to the plugin to format the data.

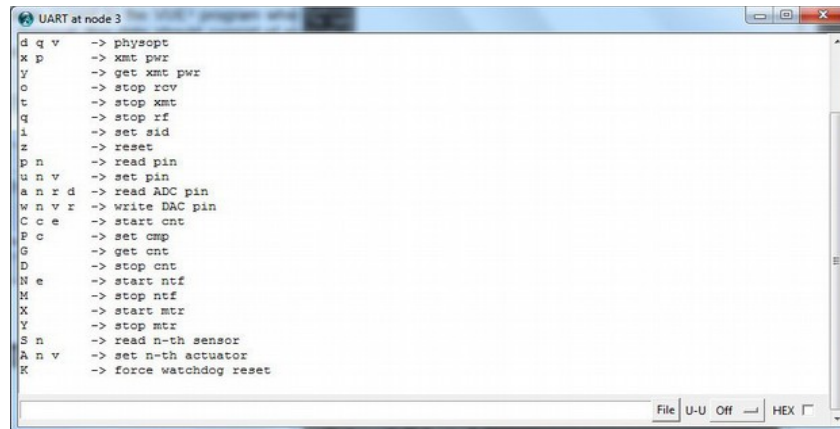


Figure 7: A UART window.

The ascii/hex variants of UART are independent of the “ascii/hex” coding discussed in Section 4.5. In this place, “hex” means hexadecimal display of the data arriving from the UART, as well as hexadecimal entry of the data to be sent to the UART, and is useful in those cases when that data are non-ASCII (e.g., the praxis is meant to communicate with some program using binary data, and we want to manually enter/view that data). A similar effect will be achieved when the UART coding is “hex” (see page 28) and the interface mode at `udaemon` is “ascii”; however, in that case, the hexadecimal coding/decoding will be done by the VUE² program. Note that double “hex,” i.e., on both sides, will have a rather confusing effect of displaying in hexadecimal the character codes of hexadecimal digits (so the input will be considerably more confusing). A plugin is recommended (Section 7.1.2) for any non-trivial non-character interfaces.

A UART connection produces a window shown in Figure 7. It looks like a straightforward terminal emulator, with the text area at the bottom used for input. The upper area is resizable and scrollable. It stores the last 1024 lines written to the UART.

²⁵ This facilitates the option of sharing plugins between `pit` and `udaemon`.

²⁶ This may change if it becomes a nuisance. Note that when the model (+`udaemon`) are started by PIP [6], the two actions happen in the right order.



By checking the “hex” box at the bottom, you can switch the terminal from “ascii” to “hex” and vice versa without reconnecting. The reason why, in addition to this box, the mode can also be selected from the root window is that when the UART window is open, some text may already have been displayed on it (see the held option on page 30). The mode switch only affects the data to be displayed in the future, not that already present on the screen. The “hex” box does not appear in the plug variant of the UART window.

A line typed into the bottom text area is sent to the VUE² program when you hit the Enter key. For the “hex” mode, this data should consist of pairs of hexadecimal digits optionally separated by spaces. Only the binary data represented by those digits will be sent to the VUE² program.

The File button appearing to the left of U-U (and to the right of the input field) can be used to open a file where the data written to the UART will be stored. Once such a file has been opened, the button label changes to “Stop”. When you press it, you will close the file and terminate the logging of the UART data.

When a node is in power-down state, its UART window receives gray background. The UART is not locked (data can be entered into the bottom entry line), but no input will ever arrive from the node. The entered data propagates over to the simulator (so it isn't stuck in the socket buffer), but is ignored there. Note that this mimics the real-life behavior of a UART interface with nobody listening at the other end. Timed input (which practically never makes sense over an agent connection) is an exception (see Section 6.1).

7.1.1 Connecting virtual UARTs to real devices

The U-U button (whose default state is Off) allows you to interface the UART to a real serial port (which may be a COM port on Windows or a tty device on Unix). Under Cygwin, as of version 1.7.13, if native Tcl/Tk is used to run PicOS scripts [2], the COM ports are emulated by Unix-like devices with COM1 mapped to /dev/ttyS0, COM2 to /dev/ttyS1, and so on (note the mildly confusing shift by one), so the device names look pretty close on both systems. You can press the button and select one of the generic devices available on the pop-up list. You can also select “Scan” (the second entry from the top), which will tell the program to scan for responsive devices and replace the generic list with the list of devices that can actually be opened at the moment.

Some of the devices on the menu (the so-called pseudo-ttys) are virtual and represent transparent pairs of devices. With their assistance, you can have real-life OSS programs talk to PicOS praxes executed under VUE² (with the OSS program talking to the one end of the respective pair and the node's UART being connected to the other).

In directory PICOS/Linux (of the PicOS package, not VUE²), you will find a file named nullmodem.c, which compiles trivially²⁷, e.g.,

```
gcc -o nm nullmodem.c
```

When you run the resulting executable, it will create two pseudo-ttys, show them to you, e.g.,

```
TTY name: /dev/pts/7
TTY name: /dev/pts/6
```

and, from that point on, act as a forwarder between them. One of those pseudo-ttys should then be selected from the U-U menu of the UART window, while the other can be opened by the OSS program. The formal baud rates used at the two ends don't have to match.

If udaemon runs under a non-native version of Tcl/Tk [2],²⁸ it will use Windows names for the serial devices (COM1, COM2, and so on). The virtual pairs are then represented by devices

²⁷ In the present version of PicOS, the nullmodem program is automatically put in the user's BIN directory, so it can be invoked directly under Linux and Cygwin.

²⁸ That was the default setup for Cygwin < 1.7.13 and is now considered obsolete.



named CNCA0, CNCB0, CNCA1, CNCB1, etc.²⁹ In *udaemon*, you should open one device of a pair, e.g., CNCB1, with the other device, CNCA1 (in this case) being used by the OSS program.

When a virtual UART of *udaemon* is connected to a real serial device, the UART window mirrors the exchange between the node and the program attached to the other end of the real port. The input field also works in that mode (your entries will be interleaved with any data arriving from the real UART), as does the HEX checkbox.

7.1.2 *UART plugins*

You can provide private functions for interpreting UART data arriving from (possibly selected) nodes as well as preprocessing the user input entered into the UART window. The file with such functions can be provided to *udaemon* with the *-P* option (Section 7).

The plugin file should contain a Tcl script defining the following functions:

```
proc vplug_init { nn hn tp tag } { ... }
```

The function is called on every connection to a UART and its purpose is to initialize the plugin for the connection. The first three arguments are (in this order): the (absolute) node number, the node host ID, and the node's type label. The three items are derived from the node's signature (Section 6.1). The last argument is a tag to be used in subsequent operations addressed to the same session (node). Note that the plugin may want to handle multiple UART connections simultaneously.

If the plugin doesn't want to handle the specific connection, the above function should return zero. In that case, *udaemon* will be handling the connection as usual, without involving the plugin any farther. Otherwise, i.e., when the function returns nonzero, three more functions become relevant:

```
proc vplug_close { tag } { ... }
```

This function will be called at the end of a session handled by the plugin (when the connection has been closed). The argument is the session tag received by *vplug_open*. The function is not expected to return any value.

```
proc vplug_receive { bytes tag hex } { ... }
```

The function is called whenever data arrives from the UART. The first argument contains the block of data (a raw string of bytes), the second argument is the session tag, and the last argument is a 0/1 flag indicating whether the UART formally operates in the "hex" mode. If the function returns a nonempty string, that string will substitute for the originally received sequence of bytes and the processing will continue as usual. If the string returned by the function is empty, then the processing of the received sequence of bytes ends at the plugin. For example, here is a void receive function:

```
proc vplug_receive { bytes tag hex } {  
    return $bytes  
}
```

This function intercepts user entries into the UART terminal:

```
proc vplug_input { text tag } { ... }
```

and is called whenever the user enters anything into the entry widget at the bottom of the UART window (Section 7.1). The first argument is a variable name, so the function body should begin with:

```
proc vplug_input { text tag } {  
    upvar $text data  
    ...
```

²⁹ See [2] for pointers to the requisite driver for those devices. The bad news is that those drivers don't work under Windows 8.1.



```
}
```

The variable itself contains the text entered by the user. If the function returns nonzero, the text will not be submitted any further, i.e., its processing will end at the plugin. Otherwise, the function can modify the original text (overwrite the variable) and return zero which will cause the (possibly modified) text to be handled as usual, i.e., sent to the node.

The plugin can take advantage of these two functions provided by `udaemon`:

```
proc term_output { text tag } { ... }
```

The function writes the text argument to the UART terminal of the session. A newline character must be explicitly included at the end of every line.

```
proc uart_send { text tag } { ... }
```

The function writes the first argument string to the UART. The string is sent raw without any preprocessing.

7.2 The PINS interface

Similar to UART, this interface requires a valid node number. Following a successful connection, a window like the one shown in Figure 8 will pop up on the screen.

The three rows of boxes at the top reflect the current status of the pins, with one column corresponding to one pin. Only the bottom row is clickable, and only if the letter in the upmost box of the column is I, which means that the pin has been set by the praxis to "input." For such a pin, clicking on the box in the bottom row toggles the binary value of the pin. In Figure 8, pins 1, 2, 3, 6, 9 are input, pins 0, 7, 8 are output (letter O), and pins 4 and 5 are set for analog input (letter A). The full collection of characters that can appear in a bottom-row box is:

I	the pin is set for digital input
O	the pin is set for digital output
A	the pin is set for analog input
P	the pin is a pulse counter
N	the pin is a notifier
D	the pin is a DAC output
-	the pin is unused (its status field in the input data set is 0, see page 33)

The middle row shows the output value of those pins that have been set by the praxis as "output." For any other pin type, the corresponding square contains a dash. Those squares in the bottom row that do not represent input pins are disabled, i.e., clicking on them triggers no action.

A right click on a clickable pixel square has the effect of two consecutive clicks separated by a 300 ms interval. The role of this feature is to emulate pressing a button (Section 4.9).

Each ADC-capable pin has a slide widget that can be used to set the voltage on that pin. Only those pins that have been currently selected for the ADC function have their slides enabled (pins 4 and 5 in Figure 8). The value above the slide knob tells the current voltage on the pin. Finally, the DAC-capable pins have voltage display areas at the bottom. No such pins are available in Figure 8.



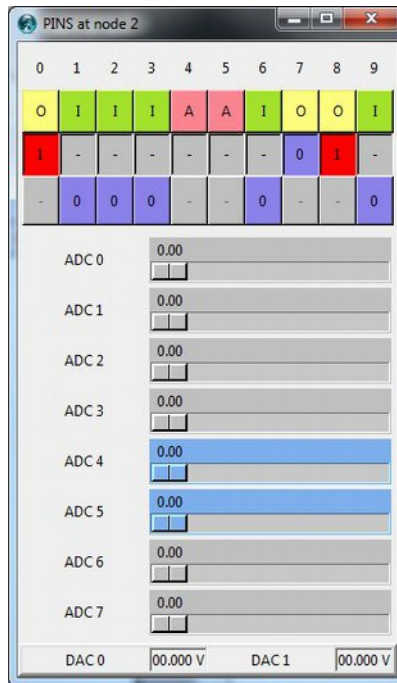


Figure 8: A PINS window.

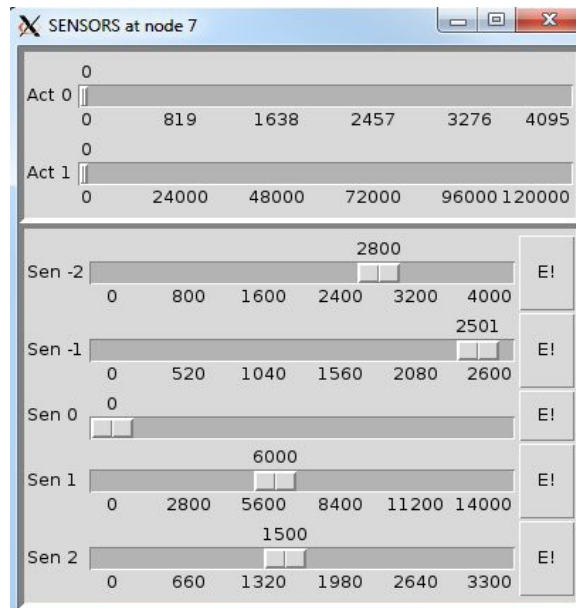


Figure 9: A SENSORS window.

Note that the praxis can dynamically redefine pins, and, for those that are output or DAC, set their values. All such changes are immediately reflected in the window. You can trigger changes in those pin values that are currently available for digital input or ADC – by clicking on a box in the bottom row or adjusting the respective slide. Such changes are immediately conveyed to the VUE² program. Slide adjustments are sent incrementally, meaning that a slow movement of the slide knob may result in multiple updates sent to the simulator.



With visualization data for udaemon, it is possible to assign symbolic (and colorful) labels to pins (see Section 7.11.7). When the node is powered down, its PINS interface becomes unusable. The window shows all pins as output with the level 0. Any ADC controls and/or DAC entries become disabled.

7.3 The SENSORS interface

Similar to PINS, this interface requires a valid node number. Following a successful connection, a window like the one shown in Figure 9 appears on the screen. The upper section displays the values of the node's actuators. There is no way to affect an actuator value from the window.

Every sensor defined at the node has a slider in the lower portion of the window. By adjusting the sliders, you can modify the sensor values. An update is sent when the mouse is released. By pressing the button labeled E! on the right of the value slider, you trigger an event on the sensor.³⁰

You can assign symbolic labels to sensors and/or actuators displayed in the window help of some simple visualization data (see Section 7.11.7).

When the node is powered down, all sensors and actuators are reset to zero and the sensor controls become disabled.



Figure 10: A LEDS window.

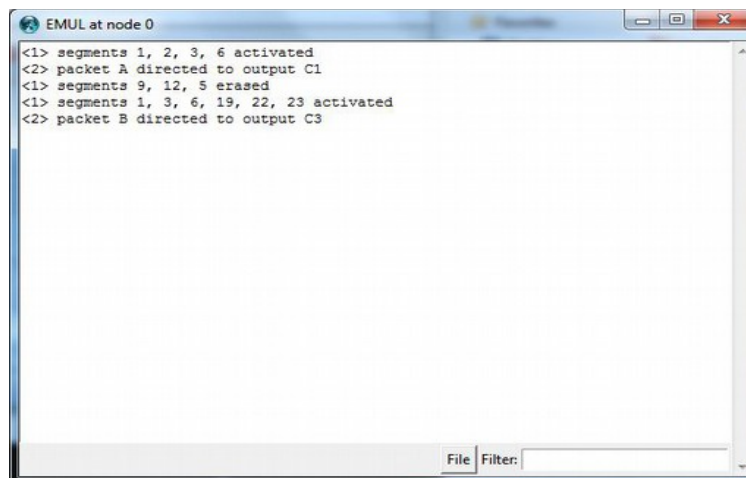


Figure 11: An EMUL window.

³⁰ Such events can be perceived by the praxis via wait_sensor.



7.4 The LEDS interface

This interface is very simple as it involves no user input. The displayed window shows one circle for each of the LEDs defined in the module, with the LEDs numbered from left to right (Error: Reference source not found). Color gray means that the LED is off, otherwise, it is on. The first five LEDs show the colors: red, green, yellow, orange and blue when lit. If there are more than five LEDs, the ones numbered 5 and up are all red.

It is possible to change the default colors of the LEDs, as well as to assign (possibly colorful) symbolic names to them. See Section 7.11.7 for details.

7.5 The EMUL interface

This interface consists of a simple text window (see Error: Reference source not found) presenting the messages issued by emul (Section 4.7).

The Filter field allows you to enter a (Tcl-style) regular expression qualifying the lines to be shown in the window (lines that do not match the expression will be ignored). The expression applies to the entire line, including the prefix tag. The File button plays the same role as in the UART window (see page 59).

7.6 The ROAMER interface

This interface takes no node number. Figure 12 shows a sample (vanilla) window displayed in response to a ROAMER connection, for a network consisting of 12 nodes of two types. The numbers in the lower right corner show the dimensions of the area covered by the window. The numerical identifiers associated with nodes displayed in the ROAMER window are their *local host ID's* (see Sections 4.4 and 6.9).

Several visualization enhancement are available for the ROAMER window (see Section 7). In particular, an image (from a file) can be used as the window's background. The size of such a window becomes fixed (the window cannot be resized). Otherwise, the window can be resized with the mouse. When that happens, *udaemon* will re-fit the nodes to the new size: you do not necessarily make the window cover a larger area, but rather magnify the picture. It isn't difficult to guess that by dragging a node, you will move it to a new location.³¹ If the dragging is reasonably smooth, multiple requests will be sent to the VUE² program, such that the movement will appear incremental to the model.

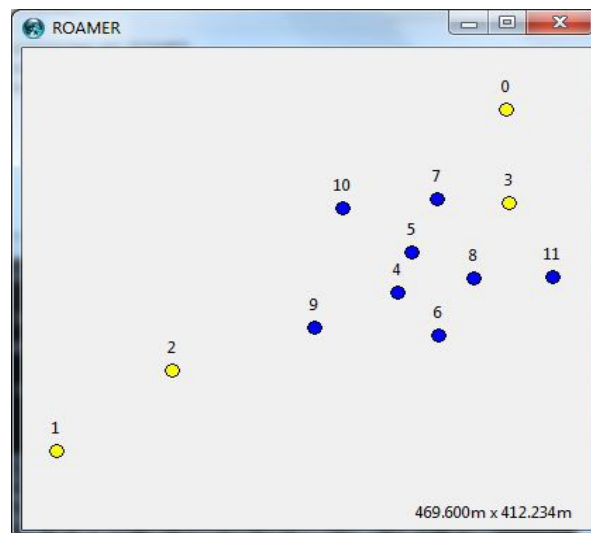


Figure 12: A (vanilla) ROAMER window.

³¹ This will only work for a movable node. A node that is non-movable will not let you be dragged.



By default, the y-coordinate starts at the bottom and grows up (the x-coordinate always starts at the left and grows to the right). The direction of the y-coordinate can be reversed with the -R option (Section 7).

Moving to the right and up is unrestricted. If you move a node beyond the window's boundary, the window will be renormalized to the new network geometry. This renormalization does not affect the window's size or shape on the screen, but the assumed dimensions of the edges. To prevent runaway renormalization (which would occur if you held the mouse outside the window's boundary), the program allows you at most to double the network dimensions with a single node drag. Moving to the left and down (or up with -R) is limited by the coordinates <0,0> (udaemon will not let you move a node below these coordinates).

To see the exact position of a node, just hover the mouse over it. The coordinates will be displayed in the lower left corner of the window along with the node's type name, as seen by VUE², which coincides with the name of the node's class. Additionally, at the end of the displayed piece of string, you will see the two identifiers of the node: the serial (SMURPH) ID followed by the local host ID (Section 4.4).

If there are multiple node types in the model, they will automatically receive different colors on the screen – up to six colors: yellow, blue, orange, red, green, gray. If there are more than six node types, all the remaining types will be gray.

Note that this only applies to the vanilla version of the window (without visualization enhancements). The default and automatic way of coloring nodes can be changed with udaemon's visualization data (see Sections 7.11.4), which also allows you, e.g., to specify a different diameter for the node circle. It is possible to color a node dynamically based on the status of its selected digital output pins or LEDs. Nodes can also be highlighted (temporarily) by the praxis to visualize interesting changes in their status (see Section 7.11.6).

There is a way to see the (straight line) distance between a selected pair of nodes. Click on the first node without dragging it, then move the mouse over the second node and click. A dashed line connecting the nodes will show up for 2 seconds with a number in the middle showing the distance between the nodes in meters.

A right click in a node's circle brings up a menu with the interface selection for the node. The selection includes all the node-relative items from the main window's interface menu shown in Figure 6.

Clicking inside the network dimension text (the right bottom corner of the ROAMER window) will open a dialog to save current node positions into a file. The information is saved in XML format, as a <locations> list (Section 4.4.7), which makes it directly usable as an included fragment of a data file (Section 4.17).

7.7 The PANEL interface

This interface takes no node number. Figure 13 shows a sample panel window. Initially, the window only displays the status of up to 16 nodes (numbered 0 to 15). More nodes can be added to the window by entering the node number in the text area at the bottom and pressing the Add button. Nodes can also be removed from the panel by pressing the blue Delete button on the right.



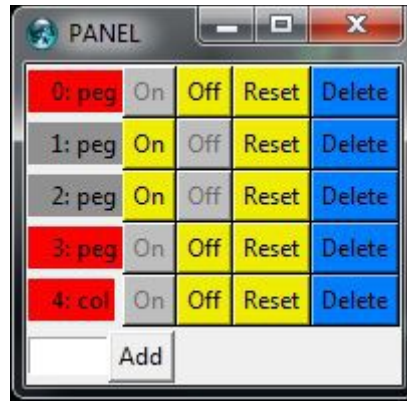


Figure 13: A PANEL window.

As shown in Figure 13, nodes 0, 3, and 4 are on, while nodes 1 and 2 are off (halted). The on status of a node is indicated by the red background color of the node's label, which shows the node number and the optional type (only present in multiprogram praxes – see Section 3.3). For the three status change buttons, color yellow means that the button is enabled. Note that Reset is always enabled: resetting an off node will also start it up and make active.

7.8 The CLOCK interface

This is a very simple interface that needs no node number. It opens a window that shows the emulated time of the model in seconds, assuming that the execution started at time 0.

7.9 The LCDG interface

This is a simple passive (reception only) interface presenting a 130x130 pixel display looking as shown in Figure 14.



Figure 14: An LCDG window.

7.10 PTRACKER interface

This interface brings in a window depicted in Figure 15. The red bar shows the current current drain (note that the scale is logarithmic), while the green bar shows the accumulated average. By pressing the small button on the right you will reset (zero out) the power tracker.

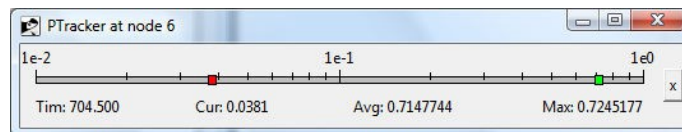


Figure 15: A PTRACKER window.



7.11 Visualization enhancements

The input data file for the simulator (or rather the input data set, as it may consist of multiple files combined together via <include> elements – see Section 4.17) is forwarded to *udaemon* upon a connection to the model (Sections 6.7, 7). The data set may contain some elements parsed exclusively by *udaemon* and bringing in a few add-ons to the standard (vanilla) interface discussed in Sections 7.1 through 7.10. Those add-ons amount to the following features:

1. Declaring the positions of selected windows on the screen. For node-relative windows (ones that may occur in multiple versions parametrized by the node number) you can declare different positions for different nodes.
2. Declaring windows to be displayed initially, immediately after starting *udaemon*. Node-relative windows are selected individually on a per-node basis. Note that 1 and 2 are useful for presentations and demonstrations.
3. Providing a background image for the ROAMER window (e.g., to show the nodes against some map of a real-life deployment area).
4. Declaring colors to be used for painting selected nodes, including highlighting and dynamic associations of colors to digital pins/LEDs at a node.
5. Declaring LED colors.
6. Introducing symbolic names (labels) to be associated with selected sensors, actuators, LEDs, and pins at selected nodes and declaring the colors of those labels and their backgrounds.
7. Declaring colors to be used for “highlighting” nodes as well as for the highlight messages (notes) displayed at the nodes.

7.11.1 Specifying initial locations for windows

A node-related window displayed by *udaemon* always applies to some module (UART, LEDS, PINS, SENSORS, LCDG, EMUL, PTRACKER) whose parameters are described either in a dedicated XML element at the node, or in a similar element appearing in <defaults> (Section 4.4). The location of a window corresponding to such a module can be specified in a <window> element inserted into the module's description. Consider this skeletal data set for an illustration:

```
<network nodes="8">
...
<nodes>
...
<node>
...
  <uart rate="9600" bsize="12">
    <input source="socket"></input>
    <window>100,210</window>
  </uart>
...
</node>
...
</nodes>
...
</network>
```

The (highlighted) <window> element inside <uart> declares the coordinates of the UART window (the left upper corner) for the given node. An element like that can be inserted (is meaningful for *udaemon*) inside <uart>, <sensors>, <pins>, <leds>, <emul>, <lcdg>, and <ptracker>, and declares the position of the respective window. It can also appear in the



<defaults> instance of any of the above – with the obvious interpretation. Note that in that case, multiple windows may fall into exactly the same location, which may make little sense.

Sometimes all (or almost all) nodes in the network use the blanket definition of a module provided in <defaults> (this is in fact quite typical for <uart>), while it would be desirable to assign the windows of their node-specific instances to different preselected locations. One solution would be to remove the <defaults> definition replacing it with individual definitions at the nodes that would only differ in the <window> element. That, however, would kill the whole idea of <defaults>. In a situation like this, i.e., when the node does not provide a specific definition of a module (which is provided in <defaults>), but you still would like to assign a unique position to the module's window, you can insert an element of this form:

```
<uart_window>100,210</uart_window>
```

inside the <node> element. The same idea applies to all node-specific modules, e.g.,

```
<node>
...
<sensors_window>450,600</sensors_window>
...
</node>
```

and so on.

For the “global” windows, which have no corresponding module definition in the data file, you declare the positions of their windows inside a special <display> element belonging directly to <network>, e.g.,

```
<network nodes="8">
  <grid>0.1m</grid>
  <tolerance quality="2">1E-4</tolerance>
  <display>
    <clock>300,400</clock>
    <panel>900,1100</panel>
    <root>10,10</root>
  </display>
  ...
</network>
```

The meaningful sub-elements of <display> are: <clock>, <panel>, <roamer>, and <root>, the last one standing for udaemon's root window.

7.11.2 Pre-displaying selected windows

If you want a particular window to show up immediately after udaemon starts, insert display="yes" as an attribute of the element used to specify the window's location, e.g.,

```
<clock display="yes">300,400</clock>
...
<node>
  <leds number="3">
    <output target="socket"/>
    <window display="yes">77,99</window>
  </leds>
  <uart_window display="yes" params="hex"/>
  ...
</node>
```

This tells udaemon to automatically issue the appropriate connection request to the simulator, establish the session, and bring the window up immediately after startup. Note that the last declaration in the above example does not specify the window's location. This is



OK: the window still will be brought up automatically; its (unspecified) location will be determined by the window manager.

The above example also illustrates the “general-purpose” params attribute applicable (in principle) to all elements specifying display parameters of a window. At present this attribute is only interpreted by the UART window where it can be used to force the variant of the UART terminal (hex, ascii, plug – see Section 7.1).

Note that setting the display attribute for the root window is redundant (that window is always displayed as soon as udaemon starts).

7.11.3 Background image for ROAMER

The <roamer> element appearing inside <display> (at the <network> level)³² may define a few additional (and optional) attributes. For example, this declaration:

```
<network nodes="8">
  <grid>0.1m</grid>
  <tolerance quality="2">1E-4</tolerance>
  <display>
    <roamer image="imgfile.gif" width="1200.0">10,20</roamer>
  </display>
  ...
</network>
```

in addition to the position of the ROAMER window, specifies a background image for the window's canvas. That file must be in one of the formats acceptable by Tk. By default, only the GIF and PPM/PGM formats are available. If you want to use other formats, e.g., jpeg, then you have to make sure that the Img package of Tcl/Tk is installed (udaemon checks for that package and uses it automatically if it happens to be available).

The location (path) of the background image file is determined by the simulator relative to the directory in which the program has been called. Note that the <roamer> element is also interpreted by the simulator (see Section 4.18).

When a background image for the ROAMER window is provided, the window becomes inflexible and cannot be resized. The program assumes that the network area covers a rectangle of the specified width (and the derived height) starting at point (0,0). Thus, you should make sure that node coordinates specified in the data file (see page 24) fall into that area. Some narrow margins within the image area (stripes at the bottom, top, left, and right) are reserved and cannot be used for node coordinates (they roughly correspond to 1/2 of the standard node circle diameter). If a node coordinate falls outside the network rectangle, udaemon will complain (with a message in the root window) and display the node at the window's boundary (such that all nodes are always shown in the window). In contrast to the flexible version of the window (without a background image), nodes cannot be moved with the mouse outside the boundary of the fixed network rectangle (even if they are movable). Note that movable nodes can still be moved anywhere by the simulator (e.g., if it runs a mobility model); if they get outside the network's rectangle, udaemon will show them at the window's boundary.

Instead of width, you can specify height (in that case the width will be derived from the image dimensions). At least one of the two dimensions (width, height) is required. You can also specify both width and height, which (if they scaling does not agree with the image dimensions) will override the image scaling.

Note that the text field of an element specifying a background image for the ROAMER can be empty, i.e., you are not obliged to specify a predefined location for the window.

³² Note that <roamer> elements (with a different meaning) can appear directly at the <network> level (Section 4.15.1).



7.11.4 Coloring nodes

By default, `udaemon` assigns some standard colors to the nodes displayed in the ROAMER window (Section 7.6), such that nodes of different types (running different programs of a multiprogram praxis [7]) are assigned different colors. Those standard colors can be changed, on a per-node basis, by inserting `<color>` elements into `<node>` elements, e.g.,

```
<nodes>
  <node number="1">
    ...
    <color solid="red"/>
    ...
  </node>
</nodes>
```

In this simple case, the (entire) node will be painted (solid) red, regardless of the node type. A `<color>` element can also be put into `<defaults>` to provide a fall back color for all nodes that do not specify their colors explicitly. Otherwise, such nodes will be painted using the vanilla rules (Section 7.6).

To make it a bit less dull, the color of a node may depend on the binary output value (0/1) of one of its digital pins or on the status of its selected LED, such that by changing the pin level or LED status the praxis will dynamically flip the node between two colors. For example, with this specification:

```
<color pin="1" on="#FF0000" off="#00FF00"/>
```

the node will appear red, if its pin number 1 is low, and green otherwise. This will only work, if the node is equipped with a PINS module (section 4.8), so it is clear what pin 1 means. The requisite pin's direction must be set to output (otherwise, its value will be assumed to be flat 0). Note that a color can be specified by name (see Appendix A) or as a hex RGB value (six hexadecimal digits preceded by #).

A node can also inherit its color from a LED, e.g.,

```
<color led="2" on="yellow" off="black"/>
```

In this case, when the LED number 2 is lit, the node will be painted yellow, and black otherwise. If the LED happens to be blinking, the node will be blinking as well (at the same rate as the LED). Note that one `<color>` element can only say one thing. If you specify multiple conflicting attributes, then `solid` takes precedence over `pin`, and `pin` takes precedence over `led`.

If you put multiple `<color>` elements into a `<node>` (this also applies to `<defaults>`), the node will be split (like a pie) into that many sections that will be independently colored according to the multiple elements, e.g.,

```
<color led="0" on="yellow" off="black"/>
<color led="1" on="red" off="gray"/>
<color pin="6" on="lavender" off="linen"/>
```

In this case, the node will be partitioned into three sections. This does not apply to `solid`: a `<color>` element with a `solid` attribute cancels all other `<color>` elements of the node and causes the node to be painted statically with the specified solid color.

The default size of the node circle may be too small to accommodate a non-trivial number of differently colored segments. The circle can be enlarged with the `nodesize` attribute of `<roamer>`, e.g.,

```
...
<display>
  <roamer ... nodesize="40">...</roamer>
</display>
```



...

The specified node size is rounded up to an even number and interpreted as the diameter of the node circle in pixels. The minimum size is 4, the maximum is 100.

When a node is powered down (e.g. from the PANEL window – Section 7.7), its color changes to solid gray.

7.11.5 Coloring LEDs

By putting a <color> element into <leds> you can assign non-standard colors to the LEDs in a pretty much obvious way, e.g.,

```
<leds number="3">
  <output target="socket"></output>
  <color on="pink" off="blue"/>
  <color on="#FF0000" off="#0000FF"/>
  <color on="white" off="black"/>
</leds>
```

In the above case, the three <color> elements apply to the three LEDs in the order of their occurrence, i.e., LED 0 will be painted pink (when on) and blue (when off), LED 1 will be painted red and blue, and LED 2 white and black. By using the index attribute of <color> you can explicitly indicate which element applies to which LED (so the permutation of the <color> elements doesn't matter), e.g., this sequence:

```
<color on="white" off="black" index="2"/>
<color on="#FF0000" off="#0000FF" index="1"/>
<color on="pink" off="blue" index="0"/>
```

has the same effect as the previous one. The idea is similar to that of deriving the node numbers (indexes) from <node> elements (see Section 4.4).

7.11.6 Highlighting

A separate component of the node coloring scheme is highlighting, i.e., assigning colors to nodes upon requests from the praxis. The praxis issues such requests by calling this function:

```
void highlight_set (lword col, double dur,
                  const char fmt, ...);
```

The simple idea is that a node invoking the above function wants to highlight itself with color col for the amount of time equal to dur seconds (note that the number can be fractional). The specified color will override (for the specified amount of time) any “normal” coloring scheme for the node as described in Section 7.11.4.

After dur seconds, the node will be automatically un-highlighted, its coloring reverted to normal. If dur is 0.0, the highlighting becomes permanent, in the sense that it will not go away automatically. It can still be canceled explicitly by the praxis by calling this function:

```
void highlight_clear ();
```

which can be also invoked to prematurely revoke a timed highlighting. The function does nothing if the node is not highlighted.

The role of the remaining arguments of highlight_set is to optionally create a “note,” i.e., a piece of text to be displayed at the highlighted node. Any arguments following fmt are converted (assuming that fmt is a format string) and combined into a single string constituting the note. If fmt is NULL, no further arguments will be sought and no note will be created. Here are two examples:

```
highlight_set (1, 1.5, "Got packet: %ld <%04x>", pktlen,
              pktID);
highlight_set (0, 0.0, NULL);
```



The color and note described by a call to `highlight_set` translate into the node's highlight attributes (see Section 6.9) arriving via the ROAMER interface as components of update (U-type) messages. In `udaemon`, they cause the node to be repainted. If the note is nonempty, it will be also shown at the node. When the highlighting expires (or is revoked by `highlight_clear`), `VUE2` will send a pertinent ROAMER update which will cause `udaemon` to remove the note and revert the node to its normal coloring (according to Section 7.11.4).

The default interpretation of the (unsigned) color (`col`) value by `udaemon` is as follows. If the value is less than 8, then it indexes the list of standard colors which are: black, gray, white, magenta, darkviolet, goldenrod, orangered, and chocolate (in this order, e.g., 2 translates into white). Otherwise, it is interpreted as a three-byte RGB value (one byte per color). This interpretation can be changed, on a per-node basis, by adding a `<highlight>` element to `<node>` (or to `<defaults>`), e.g.,

```
<node>
...
<highlight>yellow orange red green</highlight>
...
</node>
```

In the above example, the standard set of colors is redefined to yellow, orange, red, green. Now, if the specified color value is between 0 and 3 (inclusively), it will refer to one of the four standard colors, and any other value will be interpreted as RGB. An empty `<highlight>` list will make sure that all color values, including 0 (black), will be interpreted as RGB.

The `<highlight>` element accepts two independently optional (color) attributes, e.g.,

```
<highlight fg="brown" bg="yellow">
orange red green #560987 white
</highlight>
```

They refer to the colors of the highlight note (`fg`) and its background (`bg`), which default to black and "no background," respectively. When no background color is defined for the node, then the highlight note is simply displayed against the canvas content. This may make it poorly legible, especially if the canvas is covered with a vivid background image (Section 7.11.3).

The `fg/bg` attributes of `<highlight>`, if present, are also used to display the node ID, which by default is displayed as black against no background. A `<highlight>` element inserted into `<defaults>` provides a fallback definition for all nodes that do not specify the element. If no `<highlight>` element appears in `<defaults>`, then the vanilla scheme (8 standard colors, black note against no background) is used as the fallback.

7.11.7 Labels

You can assign symbolic labels to sensors, actuators, pins, and LEDs and also declare colors for those labels. Such labels will then show up in the respective windows of `udaemon` instead of the default uninformative numbers. For that, you insert `<label>` elements into the module definitions, e.g., for LEDs, you can go like this:

```
<node number="2">
...
<leds number="3">
  <output target="socket"></output>
  <label fg="green" bg="bisque">Status</label>
  <label fg="red" bg="bisque">Xmt</label>
  <label fg="orange" bg="bisque">Rcv</label>
  <color on="green" off="black"/>
  <color on="red" off="black"/>
  <color on="orange" off="black"/>
  <window display="yes">1100,210</window>
</leds>
```



...

In this comprehensive example, the LEDS module of node number 2 declares custom LED colors, a position for its window, and labels to be assigned to the LEDs. The body of a `<label>` element is the string that will be shown as the label of the corresponding LED, while the two (optional) attributes (`fg` and `bg`) specify the color for the label text and for its background, respectively. By default, a label is displayed in black against the raw background of the widget's frame.

Exactly the same way of labeling applies to PINS. Similar to `<color>`, a `<label>` element appearing within LEDS or PINS accepts an index attribute with the same interpretation as for `<color>` in LEDS (Section 7.11.5). Sensors and actuators, on the other hand, are labeled per-item, i.e., a single `<label>` element is inserted inside `<sensor>` or `<actuator>`, e.g.,

```
...
<sensors>
  <input source="socket"></input>
  <output target="socket"></output>
  <sensor index="0" vsize="2" delay="0.6">
    1024
    <label fg="pink" bg="white">Temp</label>
  </sensor>
  <sensor index="1" vsize="2" delay="0.6">
    8000
    <label fg="green" bg="white">Humid</label>
  </sensor>
  <sensor index="2" vsize="2" delay="0.6">
    2700
    <label fg="maroon" bg="white">Moist</label>
  </sensor>
  <sensor index="3" vsize="2" delay="0.6">
    2400
  </sensor>
  <sensor index="-1" vsize="2" delay="0.0" init="2600">
    2703
    <label fg="red" bg="yellow">Voltage</label>
  </sensor>
  <actuator vsize="4" delay="0.01" init="0">
    <label fg="lightblue" bg="black">Switch</label>
  </actuator>
</sensors>
...
```

An index attribute appearing in a `<label>` inside a `<sensor>` or `<actuator>` is ignored. Note that sensor 3 in the above example is assigned no label, so it will be labeled with its number.



8 References

- [1] "Programming under *PicOS*"
- [2] "Installation and Quickstart"
- [3] "PiComp: the *PicOS* Compiler"
- [4] "VNETI: Versatile NETwork Interface"
- [5] "SIDE/SMURPH: a Modeling Environment for Reactive Telecommunication Systems"
- [6] "PIP: an Integrated SDK for *PicOS*"
- [7] "mkmk: the *PicOS* Makefile Maker"
- [8] "UART Communication via VNETI (TCV)"
- [9] "Object Exchange Protocol"
- [10] "*PicOS* Pin Operations"
- [11] "Storage Operations: EEPROM, Flash, SD Cards"



9 Appendix A: symbolic color names

Name	R	G	B
AliceBlue	240	248	248
AntiqueWhite	250	235	235
AntiqueWhite1	255	239	239
AntiqueWhite2	238	223	223
AntiqueWhite3	205	192	192
AntiqueWhite4	139	131	131
aquamarine	127	255	255
aquamarine1	127	255	255
aquamarine2	118	238	238
aquamarine3	102	205	205
aquamarine4	69	139	139
azure	240	255	255
azure1	240	255	255
azure2	224	238	238
azure3	193	205	205
azure4	131	139	139
beige	245	245	245
bisque	255	228	228
bisque1	255	228	228
bisque2	238	213	213
bisque3	205	183	183
bisque4	139	125	125
black	0	0	0
BlanchedAlmond	255	235	235
blue	0	0	0
blue1	0	0	0
blue2	0	0	0
blue3	0	0	0
blue4	0	0	0
BlueViolet	138	43	43
brown	165	42	42
brown1	255	64	64
brown2	238	59	59
brown3	205	51	51
brown4	139	35	35
burlywood	222	184	184
burlywood1	255	211	211
burlywood2	238	197	197
burlywood3	205	170	170
burlywood4	139	115	115
CadetBlue	95	158	158
CadetBlue1	152	245	245
CadetBlue2	142	229	229
CadetBlue3	122	197	197
CadetBlue4	83	134	134
chartreuse	127	255	255
chartreuse1	127	255	255
chartreuse2	118	238	238
chartreuse3	102	205	205
chartreuse4	69	139	139
chocolate	210	105	105
chocolate1	255	127	127
chocolate2	238	118	118



chocolate3	205	102	102
chocolate4	139	69	69
coral	255	127	127
coral1	255	114	114
coral2	238	106	106
coral3	205	91	91
coral4	139	62	62
CornflowerBlue	100	149	149
cornsilk	255	248	248
cornsilk1	255	248	248
cornsilk2	238	232	232
cornsilk3	205	200	200
cornsilk4	139	136	136
cyan	0	255	255
cyan1	0	255	255
cyan2	0	238	238
cyan3	0	205	205
cyan4	0	139	139
DarkBlue	0	0	0
DarkCyan	0	139	139
DarkGoldenrod	184	134	134
DarkGoldenrod1	255	185	185
DarkGoldenrod2	238	173	173
DarkGoldenrod3	205	149	149
DarkGoldenrod4	139	101	101
DarkGray	169	169	169
DarkGreen	0	100	100
DarkGrey	169	169	169
DarkKhaki	189	183	183
DarkMagenta	139	0	0
DarkOliveGreen	85	107	107
DarkOliveGreen1	202	255	255
DarkOliveGreen2	188	238	238
DarkOliveGreen3	162	205	205
DarkOliveGreen4	110	139	139
DarkOrange	255	140	140
DarkOrange1	255	127	127
DarkOrange2	238	118	118
DarkOrange3	205	102	102
DarkOrange4	139	69	69
DarkOrchid	153	50	50
DarkOrchid1	191	62	62
DarkOrchid2	178	58	58
DarkOrchid3	154	50	50
DarkOrchid4	104	34	34
DarkRed	139	0	0
DarkSalmon	233	150	150
DarkSeaGreen	143	188	188
DarkSeaGreen1	193	255	255
DarkSeaGreen2	180	238	238
DarkSeaGreen3	155	205	205
DarkSeaGreen4	105	139	139
DarkSlateBlue	72	61	61
DarkSlateGray	47	79	79
DarkSlateGray1	151	255	255
DarkSlateGray2	141	238	238
DarkSlateGray3	121	205	205



DarkSlateGray4	82	139	139
DarkSlateGrey	47	79	79
DarkTurquoise	0	206	206
DarkViolet	148	0	0
DeepPink	255	20	20
DeepPink1	255	20	20
DeepPink2	238	18	18
DeepPink3	205	16	16
DeepPink4	139	10	10
DeepSkyBlue	0	191	191
DeepSkyBlue1	0	191	191
DeepSkyBlue2	0	178	178
DeepSkyBlue3	0	154	154
DeepSkyBlue4	0	104	104
DimGray	105	105	105
DimGrey	105	105	105
DodgerBlue	30	144	144
DodgerBlue1	30	144	144
DodgerBlue2	28	134	134
DodgerBlue3	24	116	116
DodgerBlue4	16	78	78
firebrick	178	34	34
firebrick1	255	48	48
firebrick2	238	44	44
firebrick3	205	38	38
firebrick4	139	26	26
FloralWhite	255	250	250
ForestGreen	34	139	139
gainsboro	220	220	220
GhostWhite	248	248	248
gold	255	215	215
gold1	255	215	215
gold2	238	201	201
gold3	205	173	173
gold4	139	117	117
goldenrod	218	165	165
goldenrod1	255	193	193
goldenrod2	238	180	180
goldenrod3	205	155	155
goldenrod4	139	105	105
gray	190	190	190
gray0	0	0	0
gray1	3	3	3
gray2	5	5	5
gray3	8	8	8
gray4	10	10	10
gray5	13	13	13
gray6	15	15	15
gray7	18	18	18
gray8	20	20	20
gray9	23	23	23
gray10	26	26	26
gray11	28	28	28
gray12	31	31	31
gray13	33	33	33
gray14	36	36	36
gray15	38	38	38



gray16	41	41	41
gray17	43	43	43
gray18	46	46	46
gray19	48	48	48
gray20	51	51	51
gray21	54	54	54
gray22	56	56	56
gray23	59	59	59
gray24	61	61	61
gray25	64	64	64
gray26	66	66	66
gray27	69	69	69
gray28	71	71	71
gray29	74	74	74
gray30	77	77	77
gray31	79	79	79
gray32	82	82	82
gray33	84	84	84
gray34	87	87	87
gray35	89	89	89
gray36	92	92	92
gray37	94	94	94
gray38	97	97	97
gray39	99	99	99
gray40	102	102	102
gray41	105	105	105
gray42	107	107	107
gray43	110	110	110
gray44	112	112	112
gray45	115	115	115
gray46	117	117	117
gray47	120	120	120
gray48	122	122	122
gray49	125	125	125
gray50	127	127	127
gray51	130	130	130
gray52	133	133	133
gray53	135	135	135
gray54	138	138	138
gray55	140	140	140
gray56	143	143	143
gray57	145	145	145
gray58	148	148	148
gray59	150	150	150
gray60	153	153	153
gray61	156	156	156
gray62	158	158	158
gray63	161	161	161
gray64	163	163	163
gray65	166	166	166
gray66	168	168	168
gray67	171	171	171
gray68	173	173	173
gray69	176	176	176
gray70	179	179	179
gray71	181	181	181
gray72	184	184	184



gray73	186	186	186
gray74	189	189	189
gray75	191	191	191
gray76	194	194	194
gray77	196	196	196
gray78	199	199	199
gray79	201	201	201
gray80	204	204	204
gray81	207	207	207
gray82	209	209	209
gray83	212	212	212
gray84	214	214	214
gray85	217	217	217
gray86	219	219	219
gray87	222	222	222
gray88	224	224	224
gray89	227	227	227
gray90	229	229	229
gray91	232	232	232
gray92	235	235	235
gray93	237	237	237
gray94	240	240	240
gray95	242	242	242
gray96	245	245	245
gray97	247	247	247
gray98	250	250	250
gray99	252	252	252
gray100	255	255	255
green	0	255	255
green1	0	255	255
green2	0	238	238
green3	0	205	205
green4	0	139	139
GreenYellow	173	255	255
grey	190	190	190
grey0	0	0	0
grey1	3	3	3
grey2	5	5	5
grey3	8	8	8
grey4	10	10	10
grey5	13	13	13
grey6	15	15	15
grey7	18	18	18
grey8	20	20	20
grey9	23	23	23
grey10	26	26	26
grey11	28	28	28
grey12	31	31	31
grey13	33	33	33
grey14	36	36	36
grey15	38	38	38
grey16	41	41	41
grey17	43	43	43
grey18	46	46	46
grey19	48	48	48
grey20	51	51	51
grey21	54	54	54



grey22	56	56	56
grey23	59	59	59
grey24	61	61	61
grey25	64	64	64
grey26	66	66	66
grey27	69	69	69
grey28	71	71	71
grey29	74	74	74
grey30	77	77	77
grey31	79	79	79
grey32	82	82	82
grey33	84	84	84
grey34	87	87	87
grey35	89	89	89
grey36	92	92	92
grey37	94	94	94
grey38	97	97	97
grey39	99	99	99
grey40	102	102	102
grey41	105	105	105
grey42	107	107	107
grey43	110	110	110
grey44	112	112	112
grey45	115	115	115
grey46	117	117	117
grey47	120	120	120
grey48	122	122	122
grey49	125	125	125
grey50	127	127	127
grey51	130	130	130
grey52	133	133	133
grey53	135	135	135
grey54	138	138	138
grey55	140	140	140
grey56	143	143	143
grey57	145	145	145
grey58	148	148	148
grey59	150	150	150
grey60	153	153	153
grey61	156	156	156
grey62	158	158	158
grey63	161	161	161
grey64	163	163	163
grey65	166	166	166
grey66	168	168	168
grey67	171	171	171
grey68	173	173	173
grey69	176	176	176
grey70	179	179	179
grey71	181	181	181
grey72	184	184	184
grey73	186	186	186
grey74	189	189	189
grey75	191	191	191
grey76	194	194	194
grey77	196	196	196
grey78	199	199	199



grey79	201	201	201
grey80	204	204	204
grey81	207	207	207
grey82	209	209	209
grey83	212	212	212
grey84	214	214	214
grey85	217	217	217
grey86	219	219	219
grey87	222	222	222
grey88	224	224	224
grey89	227	227	227
grey90	229	229	229
grey91	232	232	232
grey92	235	235	235
grey93	237	237	237
grey94	240	240	240
grey95	242	242	242
grey96	245	245	245
grey97	247	247	247
grey98	250	250	250
grey99	252	252	252
grey100	255	255	255
honeydew	240	255	255
honeydew1	240	255	255
honeydew2	224	238	238
honeydew3	193	205	205
honeydew4	131	139	139
HotPink	255	105	105
HotPink1	255	110	110
HotPink2	238	106	106
HotPink3	205	96	96
HotPink4	139	58	58
IndianRed	205	92	92
IndianRed1	255	106	106
IndianRed2	238	99	99
IndianRed3	205	85	85
IndianRed4	139	58	58
ivory	255	255	255
ivory1	255	255	255
ivory2	238	238	238
ivory3	205	205	205
ivory4	139	139	139
khaki	240	230	230
khaki1	255	246	246
khaki2	238	230	230
khaki3	205	198	198
khaki4	139	134	134
lavender	230	230	230
LavenderBlush	255	240	240
LavenderBlush1	255	240	240
LavenderBlush2	238	224	224
LavenderBlush3	205	193	193
LavenderBlush4	139	131	131
LawnGreen	124	252	252
LemonChiffon	255	250	250
LemonChiffon1	255	250	250
LemonChiffon2	238	233	233



LemonChiffon3	205	201	201
LemonChiffon4	139	137	137
LightBlue	173	216	216
LightBlue1	191	239	239
LightBlue2	178	223	223
LightBlue3	154	192	192
LightBlue4	104	131	131
LightCoral	240	128	128
LightCyan	224	255	255
LightCyan1	224	255	255
LightCyan2	209	238	238
LightCyan3	180	205	205
LightCyan4	122	139	139
LightGoldenrod	238	221	221
LightGoldenrod1	255	236	236
LightGoldenrod2	238	220	220
LightGoldenrod3	205	190	190
LightGoldenrod4	139	129	129
LightGoldenrodYellow	250	250	250
LightGray	211	211	211
LightGreen	144	238	238
LightGrey	211	211	211
LightPink	255	182	182
LightPink1	255	174	174
LightPink2	238	162	162
LightPink3	205	140	140
LightPink4	139	95	95
LightSalmon	255	160	160
LightSalmon1	255	160	160
LightSalmon2	238	149	149
LightSalmon3	205	129	129
LightSalmon4	139	87	87
LightSeaGreen	32	178	178
LightSkyBlue	135	206	206
LightSkyBlue1	176	226	226
LightSkyBlue2	164	211	211
LightSkyBlue3	141	182	182
LightSkyBlue4	96	123	123
LightSlateBlue	132	112	112
LightSlateGray	119	136	136
LightSlateGrey	119	136	136
LightSteelBlue	176	196	196
LightSteelBlue1	202	225	225
LightSteelBlue2	188	210	210
LightSteelBlue3	162	181	181
LightSteelBlue4	110	123	123
LightYellow	255	255	255
LightYellow1	255	255	255
LightYellow2	238	238	238
LightYellow3	205	205	205
LightYellow4	139	139	139
LimeGreen	50	205	205
linen	250	240	240
magenta	255	0	0
magenta1	255	0	0
magenta2	238	0	0
magenta3	205	0	0



magenta4	139	0	0
maroon	176	48	48
maroon1	255	52	52
maroon2	238	48	48
maroon3	205	41	41
maroon4	139	28	28
MediumAquamarine	102	205	205
MediumBlue	0	0	0
MediumOrchid	186	85	85
MediumOrchid1	224	102	102
MediumOrchid2	209	95	95
MediumOrchid3	180	82	82
MediumOrchid4	122	55	55
MediumPurple	147	112	112
MediumPurple1	171	130	130
MediumPurple2	159	121	121
MediumPurple3	137	104	104
MediumPurple4	93	71	71
MediumSeaGreen	60	179	179
MediumSlateBlue	123	104	104
MediumSpringGreen	0	250	250
MediumTurquoise	72	209	209
MediumVioletRed	199	21	21
MidnightBlue	25	25	25
MintCream	245	255	255
MistyRose	255	228	228
MistyRose1	255	228	228
MistyRose2	238	213	213
MistyRose3	205	183	183
MistyRose4	139	125	125
moccasin	255	228	228
NavajoWhite	255	222	222
NavajoWhite1	255	222	222
NavajoWhite2	238	207	207
NavajoWhite3	205	179	179
NavajoWhite4	139	121	121
navy	0	0	0
NavyBlue	0	0	0
OldLace	253	245	245
OliveDrab	107	142	142
OliveDrab1	192	255	255
OliveDrab2	179	238	238
OliveDrab3	154	205	205
OliveDrab4	105	139	139
orange	255	165	165
orange1	255	165	165
orange2	238	154	154
orange3	205	133	133
orange4	139	90	90
OrangeRed	255	69	69
OrangeRed1	255	69	69
OrangeRed2	238	64	64
OrangeRed3	205	55	55
OrangeRed4	139	37	37
orchid	218	112	112
orchid1	255	131	131
orchid2	238	122	122



orchid3	205	105	105
orchid4	139	71	71
PaleGoldenrod	238	232	232
PaleGreen	152	251	251
PaleGreen1	154	255	255
PaleGreen2	144	238	238
PaleGreen3	124	205	205
PaleGreen4	84	139	139
PaleTurquoise	175	238	238
PaleTurquoise1	187	255	255
PaleTurquoise2	174	238	238
PaleTurquoise3	150	205	205
PaleTurquoise4	102	139	139
PaleVioletRed	219	112	112
PaleVioletRed1	255	130	130
PaleVioletRed2	238	121	121
PaleVioletRed3	205	104	104
PaleVioletRed4	139	71	71
PapayaWhip	255	239	239
PeachPuff	255	218	218
PeachPuff1	255	218	218
PeachPuff2	238	203	203
PeachPuff3	205	175	175
PeachPuff4	139	119	119
peru	205	133	133
pink	255	192	192
pink1	255	181	181
pink2	238	169	169
pink3	205	145	145
pink4	139	99	99
plum	221	160	160
plum1	255	187	187
plum2	238	174	174
plum3	205	150	150
plum4	139	102	102
PowderBlue	176	224	224
purple	160	32	32
purple1	155	48	48
purple2	145	44	44
purple3	125	38	38
purple4	85	26	26
red	255	0	0
red1	255	0	0
red2	238	0	0
red3	205	0	0
red4	139	0	0
RosyBrown	188	143	143
RosyBrown1	255	193	193
RosyBrown2	238	180	180
RosyBrown3	205	155	155
RosyBrown4	139	105	105
RoyalBlue	65	105	105
RoyalBlue1	72	118	118
RoyalBlue2	67	110	110
RoyalBlue3	58	95	95
RoyalBlue4	39	64	64



SaddleBrown	139	69	69
salmon	250	128	128
salmon1	255	140	140
salmon2	238	130	130
salmon3	205	112	112
salmon4	139	76	76
SandyBrown	244	164	164
SeaGreen	46	139	139
SeaGreen1	84	255	255
SeaGreen2	78	238	238
SeaGreen3	67	205	205
SeaGreen4	46	139	139
seashell	255	245	245
seashell1	255	245	245
seashell2	238	229	229
seashell3	205	197	197
seashell4	139	134	134
sienna	160	82	82
sienna1	255	130	130
sienna2	238	121	121
sienna3	205	104	104
sienna4	139	71	71
SkyBlue	135	206	206
SkyBlue1	135	206	206
SkyBlue2	126	192	192
SkyBlue3	108	166	166
SkyBlue4	74	112	112
SlateBlue	106	90	90
SlateBlue1	131	111	111
SlateBlue2	122	103	103
SlateBlue3	105	89	89
SlateBlue4	71	60	60
SlateGray	112	128	128
SlateGray1	198	226	226
SlateGray2	185	211	211
SlateGray3	159	182	182
SlateGray4	108	123	123
SlateGrey	112	128	128
snow	255	250	250
snow1	255	250	250
snow2	238	233	233
snow3	205	201	201
snow4	139	137	137
SpringGreen	0	255	255
SpringGreen1	0	255	255
SpringGreen2	0	238	238
SpringGreen3	0	205	205
SpringGreen4	0	139	139
SteelBlue	70	130	130
SteelBlue1	99	184	184
SteelBlue2	92	172	172
SteelBlue3	79	148	148
SteelBlue4	54	100	100
tan	210	180	180
tan1	255	165	165
tan2	238	154	154
tan3	205	133	133



tan4	139	90	90
thistle	216	191	191
thistle1	255	225	225
thistle2	238	210	210
thistle3	205	181	181
thistle4	139	123	123
tomato	255	99	99
tomato1	255	99	99
tomato2	238	92	92
tomato3	205	79	79
tomato4	139	54	54
turquoise	64	224	224
turquoise1	0	245	245
turquoise2	0	229	229
turquoise3	0	197	197
turquoise4	0	134	134
violet	238	130	130
VioletRed	208	32	32
VioletRed1	255	62	62
VioletRed2	238	58	58
VioletRed3	205	50	50
VioletRed4	139	34	34
wheat	245	222	222
wheat1	255	231	231
wheat2	238	216	216
wheat3	205	186	186
wheat4	139	126	126
white	255	255	255
WhiteSmoke	245	245	245
yellow	255	255	255
yellow1	255	255	255
yellow2	238	238	238
yellow3	205	205	205
yellow4	139	139	139
YellowGreen	154	205	205

