THAWS: Automated Wireless Sensor Network Development And Deployment

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Abstract: - This research focuses on the design and implementation of a tool to speed-up the development and deployment of heterogeneous wireless sensor networks. The THAWS (Tyndall Heterogeneous Automated Wireless Sensors) tool can be used to quickly create and configure application-specific sensor networks. THAWS presents the user with a choice of options, in order to characterise the desired functionality of the network. With this information, THAWS generates the necessary code from pre-written templates and well-tested, optimized software modules. This is then automatically compiled to form binary files for each node in the network. Wireless programming of the network completes the task of targeting the wireless network towards a specific sensing application. THAWS is an adaptable tool that works with both homogeneous and heterogeneous networks built from wireless sensor nodes that have been developed in the Tyndall National Institute.

Key-Words: - Wireless sensor networks, Automated application development, Code generation

1 Introduction

A Wireless Sensor Network (WSN) is made from a potentially large number of sensor nodes that are capable of communicating wirelessly. The sensor nodes must be inexpensive to enable a wide deployment that can record sensor data with a high spatial and temporal resolution. The nodes must also have a small physical size and have a long lifetime to allow them to be used in a large number of applications. This paper focuses on networks that take sensor readings from many nodes and transmit them back through the network to a gateway node that can be connected to a PC. The sensor data can then be analysed. Such a network can perform many tasks, such as water quality monitoring [1], or ensuring efficient and safe manufacturing plants [2].

Each node in a WSN can be viewed as being made from a number of hardware components, as shown in Fig. 1. The node is built by combining these components or a subset of these components. The target application should be considered in the selection of each component in a node, to ensure the desired performance and lifetime of the system.

To create the optimum network for a particular application, it may be beneficial to have many different types of nodes with different functions that together create a single heterogeneous network. One reason for this is that nodes can have different functions depending on what type of sensors they are connected to. A second reason is that, to save cost, each node should only have the minimum hardware required to perform its task. If a node only has to take a reading every 10 seconds and then transmit it, a very low-powered processor is sufficient. Conversely, for more advanced tasks, a more powerful processor is required. Routing in large networks, encryption, data compression, and error correction are advanced tasks that are not possible to implement on a very low-powered processor.

1.1 WSN Application Development

The hardware developments in miniaturising sensors and improved energy efficiency of components, have enabled research on software suitable for WSNs. New communication algorithms have been designed for large-scale wireless networks, where energy consumption is an important factor and low-power radios create unreliable connectivity [3]. Other research is focusing on operating systems that can run on very limited processors, and still provide support for applications, such as TinyOS [4].

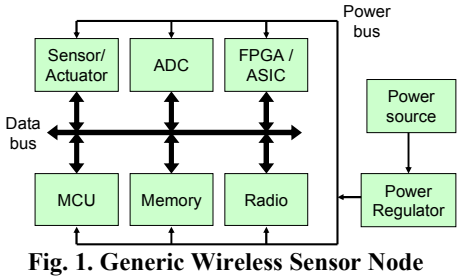

Fig. 1. Generic Wireless Sensor Node

There are also difficulties creating applications for WSNs. Currently, many applications are developed using low-level programming languages such as C or nesC [5]. To develop a new application requires someone with experience in programming with these languages. It also requires being familiar with the various libraries available. This makes fast development and deployment of networks difficult.

There also can be other difficulties in developing applications for WSNs. To save energy, code is often event-driven. For example, the node can be woken up by a timer, take a reading, and then go back into a sleep mode. The event-driven approach is implemented through the use of interrupts which creates the opportunity for corrupted data due to race-conditions if the programmer is not careful [6].

A more fundamental difficulty is created by the distributed nature of WSNs. Some applications can be simplified by assuming that all nodes are identical. However, as described above, real networks may be heterogeneous so as to minimize cost while retaining functionality where required. Developing an application for such a network involves developing different code to execute on each node. This is time-consuming and the application logic becomes separated into many different files, making debugging and future development difficult.

This paper introduces a system called THAWS that simplifies application development for WSNs. THAWS allows users to create applications for running on heterogeneous networks, as well as homogeneous networks. The user can specify what they want the network to do, and its associated constraints, without worrying about how this will be implemented. The network builds itself, generating the necessary code and programming the nodes appropriately.

This paper first briefly discusses the nodes used. Then the design and use of the tool to help rapidly develop WSN applications is presented. The tool is analysed and compared with other similar systems. Finally, future work and conclusions are discussed.

2 Implementation

The tool is implemented to work on a two-tiered network with two different classes of nodes, as shown in Fig. 2. The first node is small in size, inexpensive, and has very low-power energy consumption. The second node is bigger in size, and also more expensive. However it has more processing capability. They are used to build a heterogeneous network where the larger, more powerful node can provide the backbone of the network, and do any heavy information processing that is required. In the THAWS system, each larger node supports a cluster of smaller of the smaller, cheaper nodes that can be used for sensor interfacing and more simple tasks. The larger node is suited to higher-powered long-distance communication between clusters as they can have a large battery. The two nodes are described in the next section.

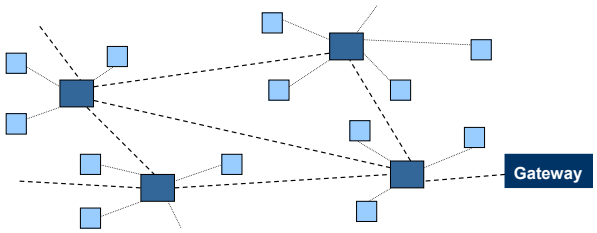

Fig. 2. Two-tiered heterogeneous network

2.1 Tyndall Wireless Sensor Nodes

In the Tyndall National Institute a number of different nodes have been developed. Along with various application specific nodes, two modular nodes have been designed with a size of 10mm by 10mm [7], and 25mm by 25mm [8]. These are referred to as the 10mm and 25mm nodes. Both these nodes are made up of a number of different layers. Each node has a processing and transceiver layer. Sensor layers can then be connected with application specific sensors, for example temperature sensors, humidity sensors, accelerometers, gyroscopes, etc. This modular approach allows the nodes to be used to build sensor networks for many applications. The 10mm and 25mm nodes are shown in Fig. 3.

The 25mm node has more powerful processing capabilities than the 10mm node. This is provided by a layer with an Atmel ATmega128 microcontroller with 128kB of program memory. There is also an FPGA layer that can be used for intensive processing, such as forward error

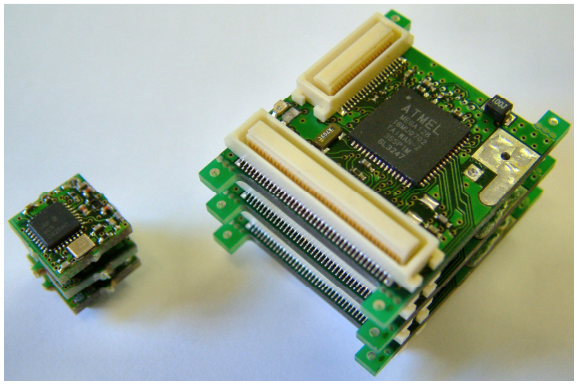

Fig. 3. 10mm and 25mm modular Tyndall nodes

correction, cryptography, or image processing. The 25mm has a number of different layers for RF communications. In the 2.45GHz frequency band there is a layer using a Nordic nRF2401 transceiver and another layer using an Ember EM2420 ZigBee compatible transceiver. There is also a 433/868/915 MHz layer using a Nordic nRF905 transceiver, which allows a longer range compared to the 2.45GHz options. The drawback is that bandwidth is limited to 50kbps, compared to 1000kbps for the Nordic nRF2401 [9].

For the 10mm node, there is currently a single transceiver layer. This uses a Nordic nRF9E5 chip. This chip has a radio that is compatible with the Nordic nRF905 so this allows heterogeneous networks to be built. This chip also has an integrated 8051-compatible microcontroller with a limited 4kB program memory. The small size of the 10mm nodes allows a greater range of applications, for example it can be more easily embedded into clothing, or it can be used in medical applications. The 10mm node is also cheaper due to reduced PCB size, and lower component count. Using the 10mm nodes together with the more powerful 25mm nodes allows a lot of flexibility in building WSNs suitable for a wide range of applications.

2.2 THAWS Overview

The core of the THAWS system is an application generating tool. An overview of how this works is illustrated in Fig. 4.

The tool has two inputs. The first of these is a software library containing modules of code that act as primitives in building up a WSN application. Some of the modules are in the form of templates that are customised for varying application requirements. The second input into the tool is a description of the desired application. This defines the functionality of the network, and also constraints. For example the type of sensors, number of nodes etc. and network topology are declared.

Using these two inputs, the tool then outputs binary program images for each node in the network. This is done by first producing C files and then compiling these using the appropriate compiler. The use of wireless in-network programming then allows the network to be programmed or reprogrammed/reconfigured to have the desired functionality.

2.3 Software Code Library

The performance and efficiency of the final developed application will depend greatly on the performance and efficiency of the software library. Both energy efficiency and the memory (RAM and ROM) footprints were considered when creating the library. The limited ROM of the 10mm node especially requires efficient code. The code is also tested and debugged thoroughly.

Some common modules are required in each WSN application. Modules are needed to interface to radios, and interface to sensors. This code for interfacing to hardware follows HAL (Hardware Abstraction Layer) principles [10]. A common interface is defined for hardware that has similar functionality. For example each of the 4 radios used by Tyndall nodes share a common low-level interface. This interface is currently used to implement star or tree networks. Currently there is a very simple MAC layer on top of this low level layer that supports addressing, collision avoidance, and tree networks with a predefined topology. This MAC layer is independent of radio or microcontroller, due to the use of a HAL.

For interfacing with sensors, modules have been developed that use I2C, SPI, and UART protocols to interfacing with digital sensors. Using integrated ADCs, analogue sensors can also be interfaced with.

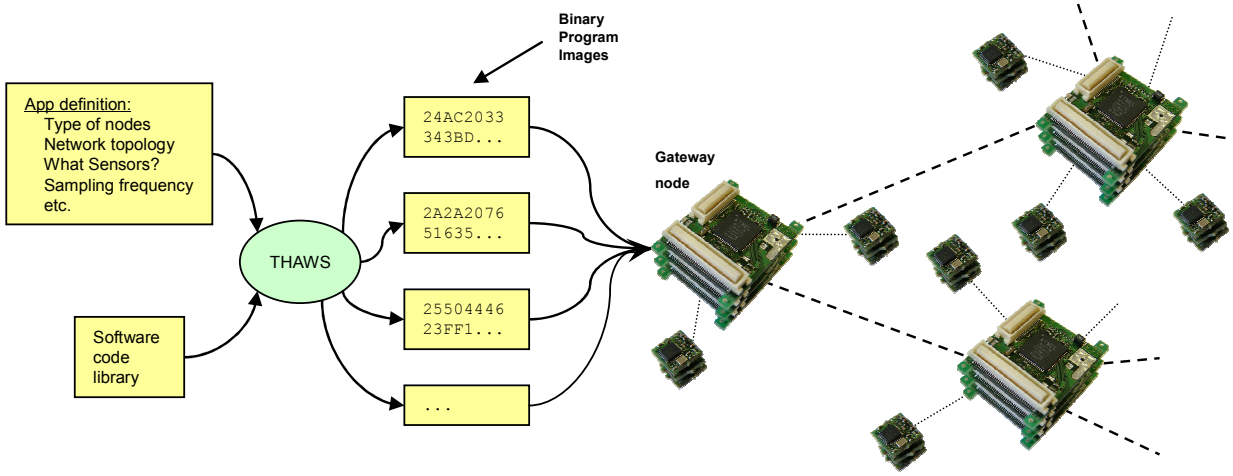

Fig. 4. Application development tool

These sensor interfaces have also been developed, so that the higher level application logic does not need to be changed if it is running on a 25mm node or a 10mm node.

In addition to communications and sensing, code has also been developed for timers and buffers, which are common building blocks that make up a WSN application Timers are used to enable low-power sleep modes. The timer can run in this mode, and wakeup the node when required, for example when a sensor reading needs to be taken. Buffers can be used for temporarily storing sensor readings either in RAM for volatile storage or in EEPROM/Flash for persistent storage.

Higher level software modules tie together the hardware interfacing code to produce an application. These are in the form of application templates which can be automatically modified to produce a specific application. For example setting the address of each node in the network, or including the appropriate files for the attached hardware.

The software modules which are core to the THAWS tool have been tested in a real-world deployment. The SmartCoast project [1] has been monitoring water quality (pH, conductivity, turbidity, depth, temperature) in the River Lee in Cork, Ireland for almost 12 months. In this time the only maintenance required was to periodically clean the sensors, and recharge the battery.

2.4 Application Generation

The part of the THAWS system that is most visible to the user is a wizard tool. This is currently implemented as a console application that asks the user a number of questions about the network, as shown in Fig. 5. This information is then used in the task of code generation.

THAWS has knowledge of which software modules are needed for each node depending on what options the user picks. It also knows how to modify application templates to have the needed functionality. This is done by substituting marked text in the application template with code to create valid C files. THAWS searches through the source file until it finds a variable marked with the prefix "THAWS_VAR_". For example to support tree routing each node is given the required addressing information, e.g. THAWS_VAR_PARENT_ADDR. The variables can have default values, so that the code can be compiled by hand without using the THAWS tool for testing and debugging purposes.

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» How many nodes?
» What type are they?
» What type of radio?
» What sensors are attached?
» How often to take readings?
» What readings to report?
» What is the network topology?
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Fig. 5. Questions to generate network specification

The use of HALs for interfacing with the radio and sensors simplifies the code generation. Different modules that present the same interface can be included without changing any other code. For example the code for any radio can be linked to without any other modifications because they each have the same functions.

The compiling and linking processes, that select which code will be included for each node in the network are all controlled by THAWS to output the required binary files. This is done by generating makefiles [11] with the necessary rules for including the correct code modules and using the appropriate compiler.

THAWS also outputs a text file with a formal description of the network. This can be used as an input to the tool to regenerate the same network. It can also be modified to change the functionality.

2.5 Wireless Programming

After the code generation, the binary files can be programmed onto the network wirelessly. This avoids the time-consuming task of manually connecting each node to a PC and programming it. This can be especially difficult if a network has been deployed in a harsh environment, such as marine monitoring.

To support wireless programming each application has the ability to receive a new program binary image and write this to its own program memory. When a complete program has been written to the memory, the node can restart itself and execute the new program. With the 10mm node there is an external EEPROM which provides persistent storage of the program. When the node is powered up, the microcontroller copies from the EEPROM to an internal RAM that is used solely for program code. As the EEPROM is only accessed at power-up, it can be easily rewritten. For the 25mm node, integrated Flash memory is used for the program code. A special area of this is reserved for a bootloader program. This bootloader program can receive data through the radio and overwrite the rest of the Flash.

3 Analysis

All programming systems must make a compromise

between the level of control and ease of use. To have no compromises on possible applications, the application can be developed in a low-level language like assembly, C, or using the TinyOS [4] system. Assemblers and C compilers are available for most platforms, so they are a possible choice for almost all platforms. However the availability of libraries will vary from platform to platform. TinyOS provides a large set of libraries to support energy-aware WSN applications and has libraries for many common tasks. With each these options a lot of care is required to create a reliable application. The programmer must be able to create energy-efficient applications, avoiding, for example, race-conditions, as discussed in the introduction.

Much effort has been spent developing systems that support easier application development for WSNs. One such system is Maté [12], which defines a list of byte-code instructions that can be used to construct wireless sensor network applications. The byte-codes can be sent to a node and will be run by an interpreter on the node. This system has the advantage of fewer lines of code then developing in C, and thus a faster application development time. It is also easier to disseminate new programs into the network, because of the small size of the byte-codes. Limitations of Maté are that the user must be familiar with the byte-codes which look like an assembly language, and also it is assumed that every node will have the same function and design.

SNQPs (Sensor Network Query Processors) [13] are another approach that provide macro-programming of the full network of nodes, from a single declaration. With a SNQP the network can be interfaced with as if it were a database. The user can then enter SQL queries which are interpreted by the network and the desired data is returned to the user.

For example: "*SELECT nodeid, temperature, FROM sensor, WHERE temperature > 20, SAMPLEPERIOD 10s"*

This will return – from each node where the *temperature* is greater than 20 °C – the *nodeid* and *temperature* reading every 10 seconds. SQL is easier to use than byte-codes as it focuses on what the user wants and not how this should be implemented. However there is still a cost in interpreting the queries, and currently the system is not designed for heterogeneous networks.

Tenet [14] is an architecture for creating two-tiered heterogeneous networks. More powerful nodes are called masters, and less-powerful nodes are motes. With Tenet, the master nodes do most of the work, and this is where the application is programmed by the user. The motes are programmed directly by the master nodes, using tasks, which are sent by the master to the mote. Each task is made up of a string of tasklets, which are simple instructions, for example sampling an ADC channel. The mote performs each tasklet and then, to complete the task, sends a response to the master. Tenet provides some support for some motes having different functionality. A task can contain predicates that must be met before the task will be executed. However this test is done on the mote so the task still has to be sent to every node, which is inefficient. A significant difference between Tenet and our system is the class of the nodes. The mote in the Tenet system is comparable in functionality to the 25mm Tyndall node. The master nodes are a PC or based on the Intel Stargate platform, which has a 32bit, 400MHz processor, and 32MB of program memory. This node is several orders of magnitude more expensive than the 25mm node.

The THAWS tool that has been presented in this paper allows fast and easy application configuration and rapid deployment of two-tiered heterogeneous, and homogeneous sensor networks. THAWS is also easy to use for non-engineers. No knowledge or embedded systems development is necessary. Our system is expressive enough to allow the fast development of any sensor data gathering application. The use of code generation, and not an interpreter, allows for greater efficiency, which is very important on severely constrained systems that must have a long life-time. The use of C code allows our system to be extended relatively easily to different platforms. It is currently working on Atmel ATmega128 and an 8051 compatible processor, which have completely different tool-chains. The Maté, SNQP, and Tenet systems all use TinyOS as a base system. Although this gives access to TinyOS's libraries, it also limits their system to TinyOS compatible platforms.

4 Future Work

Our system is presently in an early stage of development. Although it is possible to develop applications that are capable of being deployed, there a number of improvements that can be made. There is a lot of potential to research optimized algorithms for our system. The current library supports simple tasks. However it can be improved through the use of more advanced MAC algorithms, that can enable better energy efficiency as the transceiver can be in a sleep mode for more time.

Supporting in-network wireless re-programming of networks provides many difficulties. Much research has been done into solving these.

Dissemination algorithms for sending the large program code to all nodes in the network without causing network congestion have been examined [15]. Complementary research has been done into only reprogramming only the parts of the program memory that have changed [16]. This reduces the amount of data that has to be sent over the radio. However, due to its heterogeneous nature, our network will provide extra difficulties.

The THAWS system will be validated by using it to develop and configure some real WSN deployments. The Tyndall National Institute has deployments of wearable, environmental monitoring, and medical sensor networks that can be used for testing. This will give valuable information on the ease-of-use and reliability of THAWS.

5 Conclusions

We presented in this paper a new method for fast development and deployment of wireless sensor networks. The sensor networks can be heterogeneous to minimize the cost of the overall network, and also to facilitate non-uniform functionality of each node.

To support this development, the THAWS tool allows macro-programming of the entire network from a single application definition. This definition is obtained from the application developer without the need for any knowledge of software programming or embedded systems.

THAWS has been implemented to use the modular Tyndall nodes, and uses software modules that have been tested in real-world deployments.

6 Acknowledgements

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