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GINSENG: Performance Control in Wireless Sensor Networks

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***Abstract*—The goal of the GINSENG project is a performance-controlled sensor network suitable for applications with specific network performance requirements, such as plant automation and health monitoring. Any such sensor network must include a deterministic MAC protocol that can meet the application's targets in areas like delivery delays and reliability. We present a description and preliminary evaluation results of GinMAC, designed to be such a MAC protocol. Also included are details of a deployment to the GALP oil refinery in Sines, Portugal.**

I. Introduction

Most of the wireless sensor network (WSN) deployments to date have been in areas like environmental monitoring and agriculture where network performance assurances are not a requirement. The resulting architectures and protocols are not suitable for WSNs in other important areas, including plant automation and health monitoring, since they do not provide the performance assurances that are essential in these areas.

Towards this end, the primary goal of the EU-funded GINSENG project [1] are wireless sensor networks that meet application-specific performance targets and that will integrate with industry resource management systems. Our results will be proven in a real industry setting, an oil refinery in Portugal, where performance is critical.

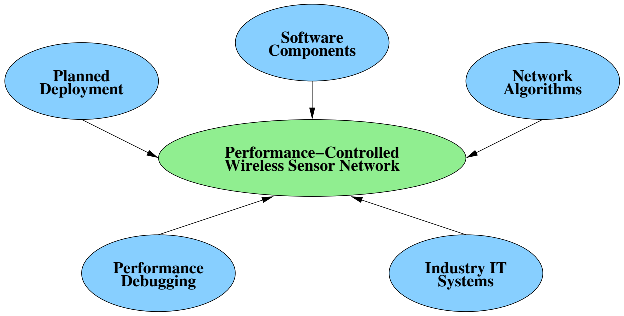


Fig. 1. The GINSENG approach.

Figure 1 depicts the GINSENG approach and its main components. Unlike applications that are based on random deployment, GINSENG assumes a carefully planned and deployed network of sensor nodes as a basis to achieve performance control. The second basis of GINSENG are software components with assured performance. This includes operating systems that execute tasks within a given time and predictable access to the radio medium by means of a MAC layer that enables access to the radio medium within a certain time bound. The third basis of GINSENG is a set of algorithms that ensure control with respect to the network topology and traffic. These three components enable the possibility of deploying sensor networks with assured performance. Due to the inherent uncertainties in WSNs e.g. node availability and the radio medium, it is possible to experience undesired changes in the operating environment, motivating the need to monitor and potentially debug the performance of the deployed system. GINSENG targets mechanisms and tools to carry out performance debugging of deployed systems and reconfiguration when given performance metrics can no longer be achieved. Another objective of GINSENG is the integration with industry IT systems.

One of the key aspects of the project is the development of GinMAC [2], a deterministic MAC protocol capable of providing performance assurances for metrics such as reliability and delivery delay. This has been the focus of much of the research to date and is detailed in this paper.

II. MAC Protocol with Deterministic Message Transport Behaviour

The GINSENG target application is devoted to monitoring and control of industrial processes, safety and pollution supervision in the GALP oil refinery. Within this refinery, there are approximately 35,000 sensors and actuators that are used to monitor and control all operations of the refinery. Messages sent by sensors to the sink and from the sink to actuators are subject to specific time bounds denoted by D_S and D_A respectively. With this target application domain and

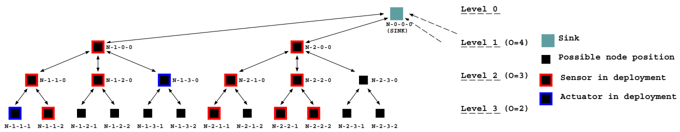


Fig. 2. Example Topology with $H = 3$ and $O_1 = 4$, $O_2 = 3$, $O_3 = 2$; $N_a = 2$ actuators and $N_s = 10$ sensors. Half of the topology is not shown as it contains no nodes.

its requirements in mind we designed GinMAC. A description of GinMAC's main components, Off-line Dimensioning and Exclusive TDMA, follows.

Off-line Dimensioning

A network dimensioning process is carried out before the network is deployed. The inputs for the dimensioning process are network and application characteristics that are known before deployment. The output of the dimensioning process is a TDMA schedule with frame length, F, which each node has to follow.

The GinMAC TDMA frame contains a number of basic slots which are selected such that within any F each sensor can send one message to the sink and the sink can transmit one unicast message to each actuator in addition to one broadcast configuration message. The GinMAC TDMA frame also contains additional slots to improve transmission reliability. Finally, the GinMAC TDMA frame may contain unused slots which are purely used to improve the duty cycle of nodes. The three types of slots within the GinMAC frame must be balanced such that the delay requirements ($F < min\{D_S, D_A\}$), reliability requirements and energy consumption requirement are met. It has to be noted that it may not be possible to find a frame that fulfils all necessary requirements. In this case, some dimensioning assumptions must be relaxed.

To determine the number of basic slots required in the GinMAC TDMA frame, a topology envelope is assumed. This topology envelope is specified as a tree rooted at the sink and described by the parameters maximum hop distance, H, and fan-out degrees $O_h (0 < h \leq H)$ at each tree level, h. The topology envelope can accommodate a maximum number of $N^{max} = \Sigma_{n=1}^{H} \Pi_{m=1}^{n} O_m$ nodes, however, in the actual deployment a number of nodes $N \leq N^{max}$ may be used. Nodes in the later deployment can take any place in the network and even move as long as the resulting deployed topology stays within the topology envelope. The maximum number of N_S^{Max} sensor nodes and N_A^{Max} actuator nodes (with $N = N_S^{Max} + N_A^{Max}$) must also be known. To determine the number of additional slots needed for reliability control, the worst-case link characteristics in the deployment area must be known. As the network is deployed in a known environment, it is possible to determine this value by measurement. The configuration of basic and additional slots determines an energy consumption baseline of nodes. By adding unused slots within the GinMAC frame, it is possible to improve upon this baseline.

An example topology with 13 nodes (a sink, ten sensors and two actuators) is shown in Figure 2.

Exclusive TDMA

GinMAC utilises TDMA slots that are used exclusively; a slot used by one node cannot be re-used by other nodes in the network. Thus, the protocol does not scale to networks with many nodes. However, this is not expected to be necessary for the given application scenario. Furthermore, in the target application scenario nodes are close together and high levels of interference would limit potential slot re-usage. Finally, exclusive slot usage allows us to construct a protocol which is relatively simple to operate and to debug. Slots have a fixed size and are large enough to accommodate a data transmission of a maximum length and an acknowledgment from the receiver. In a setting such as a refinery, each application made up of a small number of nodes would have its own network/cluster. Each cluster could operate on a different frequency to allow more applications to be supported.

Leaf nodes (level O_H) in the tree require one slot within F to send data to its parent node (level O_{H-1}). This parent node requires a slot for each child node plus a slot for forwarding its own data to its parent (level O_{H-2}). A parent's slots must be scheduled after those of its children to ensure that data can be delivered to the sink within a single frame. Figure 3 shows the slot allocation for the example in Figure 2.

III. EVALUATION

Our preliminary evaluation was carried out using the Cooja simulator included with the Contiki operating system [3]. In the simulation environment perfect communication links are used and there are no packet losses due to noisy channels. Details of a more comprehensive evaluation currently under way are given in Section IV.

X-MAC [4] is the default power saving MAC protocol included in the Contiki operating system and was used for comparison purposes.

Evaluation Setup

A small network of n = 15 nodes in a binary tree configuration with static routing is deployed. The nodes run Contiki 2.4 and use either the default X-MAC or GinMAC. GinMAC is configured such that all messages can be delivered within 1s. X-MAC is configured to use an idle duty cycle of 8% (This idle duty cycle matches the highest duty cycle observed using GinMAC). All nodes send data packets with a frequency of $1Hz \leq f \leq 0.1Hz$ to the sink. For each data reporting frequency the experiment is executed for 10 minutes. The message transfer delay D_S for all packets is recorded and the overall message reliability $\bar{R}_S$ is measured. In this setting $\bar{R}_S$ is measured as the percentage of data packets delivered to the sink. Furthermore, the nodes radio on time is recorded to determine energy consumption.

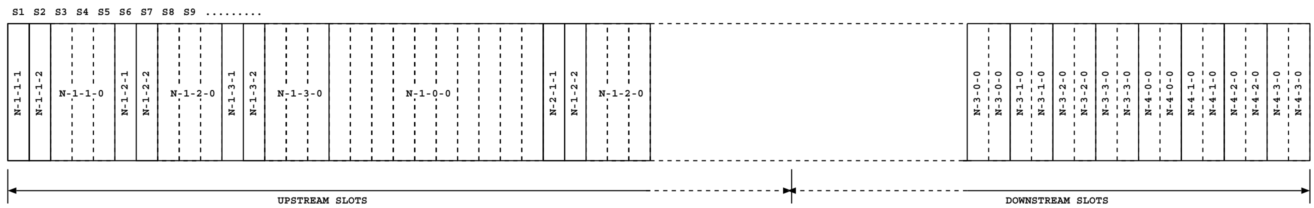


Fig. 3. Slot allocation for the example shown in Figure 2

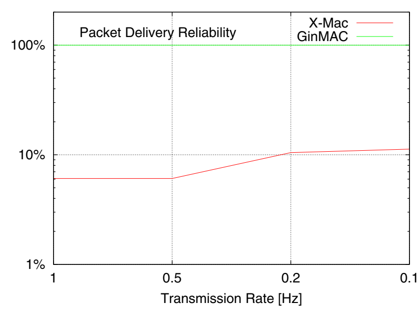
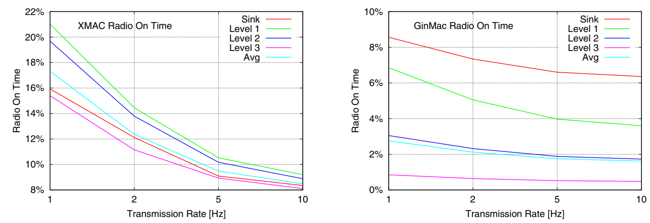


Fig. 4. Message transfer reliability $\bar{R}_S$ using X-MAC and GinMAC.



(a) Radio on time for X-MAC. (b) Radio on time for GinMAC.

Fig. 5. Energy consumption using X-MAC and GinMAC.

X-MAC Evaluation Results

Figure 4 shows the overall message reliability $\bar{R}_S$. All messages arriving at the sink have a delay of $D_S < 1s$. However, X-MAC experiences considerable losses with at most 11.2% of messages arriving at the sink. Losses are due to collisions as nodes compete for the channel. Figure 5(a) shows the energy consumption of nodes at different positions in the binary tree topology.

GinMAC Evaluation Results

Figure 5(b) shows the energy consumption of nodes at different positions in the binary tree topology. As with X-MAC all messages arriving at the sink have a delay of $D_S < 1s$, however unlike X-MAC the message delivery reliability for GinMAC of $\bar{R}_S = 100\%$ was recorded for all traffic loads, as shown in Figure 4.

Findings

The experiments show that X-MAC can not support time-critical application scenarios. At any traffic rate where contention is present X-MAC is unable to deliver data reliably. Loss rates of 94% are unacceptable for time critical applications such as industrial process automation and control. Even at modest traffic loads not more than 11.2% of data packets arrive at the sink. However, the few packets that arrive are delivered in time. Nodes using X-MAC have radio on times of over 15% at high traffic loads. GinMAC nodes have average radio on times of less than 3%. Thus, GinMAC consumes far less energy while delivering all data successfully.

IV. Evaluation at the Petrogal Refinery

A small network similar to that described in Section III is currently being deployed at the refinery in Sines. The network consists of 15 wireless sensor nodes (TelosB) equipped with sensors that can measure pipe pressure, product flow and storage tank level. All nodes are deployed in ATEX compliant configuration as required.

The network will collect data gathered by the sensors in order to evaluate the architecture and protocols we have developed in a real-world setting. Delivery delays and message losses are of particular interest.

V. Conclusions

The main goal of the GINSENG project is wireless sensor networks that provide performance assurances for important metrics such as delay and reliability which are crucial for a broad class of emerging sensor network applications. The GINSENG results will be proven in an oil refinery in Portugal. In this paper, we have presented details of GinMAC, a deterministic TDMA based MAC protocol designed for such deployments. We have also shown some promising results from a preliminary evaluation of GinMAC.

Acknowledgments

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