CLAMP: CROSS LAYER MANAGEMENT PLANE FOR LOW POWER WIRELESS SENSOR NETWORKS

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ABSTRACT

Traditional layered architectures used for wireless networks pose drawbacks in terms of performance and efficiency. The constrained resources of wireless sensor nodes such as memory, computational power, and energy motivate to modify traditional layered architectures. In this paper we present a cross layer management plane for low power wireless sensor networks which enables sensor nodes to exploit cross layer information for efficient resource utilization. A set of potential well known parameters to be used to benefit from the synergy across layers is presented. The feasibility of the concept and the advantages drawn from using cross layer information is shown by simulation.

Index Terms— *Wireless Sensor Networks, Cross Layer Design, Layered Architectures*

I.   INTRODUCTION

The advances in electronic circuitry and micro electro-mechanical systems have made it possible to build smart environments powered by sensor networks [1, 2]. Sensor networks comprise of a large number of inch sized sensor nodes. As the sensor nodes are battery operated or scavenge energy from the environment, the restricted amount of energy becomes the main issue in deployment of sensor networks.

Unlike traditional Ad hoc wireless networks, where Quality of Service (QoS), reliability and transmission delay were the main issues, sensor networks need to last months to years. The traditional layered networking approach has loopholes in terms of performance and efficiency of the system for wireless networks [3]. We propose a Cross LAyer Management Plane (CLAMP) to be integrated as an additional vertical plane to the traditional layered networking approach. CLAMP is sub module of our recently proposed protocol architecture[21], (see Fig 1.) which is similar to the traditional layered approach providing cross layer optimization benefits [4] in an optional way so that the concept of modularity of layered architectures is maintained. The idea is simple in terms of space and time complexity to be implemented in resource constrained sensor nodes. Every change in the sensor network related parameters are written to a shared database in the CLAMP by the concerned layer (owner of the parameter e.g., application layer is the owner of delay requirements related parameters). Any layer interested in any of the parameters can subscribe to that information and will be notified of changes. It can also query current value of particular parameter. The idea is to provide a list of well known parameters just like we have port numbers for well known services in TCP/IP protocol suite so that network software for different modules can be used interchangeably e.g. different routing protocols which use cross layer information can be plugged and played with out customizing other concerned layers.

Preliminary results (section V) show that implementation of CLAMP with traditional layers can prove to be very beneficial to extend the network life time.

The rest of the paper is organized as follows: Section II gives an overview of related work. Section III presents the proposed solution. Section IV discusses implementation details and preliminary results are discussed in section V. Finally, Section VI concludes the discussion with future directions.

II.   RELATED WORK

In [5], the authors propose a cross layer optimization frame with an optimization agent providing top down and bottom up feedback to different layers of the protocol stack to benefits from the current network conditions. In principal our approach is similar to the one discussed in [5], but we define a set of well-

defined parameters in advance which can affect network performance and energy utilization at run time. Knowing the set of parameters in advance, module implementations on different layers can be exchanged without any modifications in the other modules. We also keep the usage of these parameters to be optional so that if a particular module on some layer does not want to use them or a particular parameter is not available to certain module (which it intends to use), the architecture should be flexible enough to accommodate this.

In [6] the presents the benefits of cross layer feedback and related survey but do not propose a specific architecture for cross layer design.

The authors in [7] present cross layer feedback architecture for wireless networks. They introduce tuning layers (to provide interfaces to data structures stored on different layers) and optimization subsystems (algorithms for cross layer optimizations) to gain cross layer benefits. As the architecture is proposed for wireless comparatively high power mobile devices; the processing overhead of tuning layers and optimizing subsystems may not be well suited for low power wireless sensor networks.

The authors in [8] propose an Information Exchange Service (IES) to introduce cross-layer optimization. The approach is very similar to our approach but like [5] it does not provide an explicit list of parameters to be maintained by the cross layer management plane which restricts the usage of "plug and play" features. When replacing a single layer the adjacent layers have to be adjusted too. The overall protocol stack architecture is also different from the traditional approach with the introduction of data fusion and data service layers.

III. PROPOSED ARCHITECTURE

The CLAMP is sub module of our recently proposed layered protocol architecture [21] for low power wireless sensor networks shown in Figure 1. The protocol architecture is composed of traditional layers, the energy management plane (EMP), the security management plane (SMP), the node management and the CLAMP. The architecture is additionally shown with partial software to hardware mapping to clearly understand the major energy consumption components e.g. the data sampling from sensors.
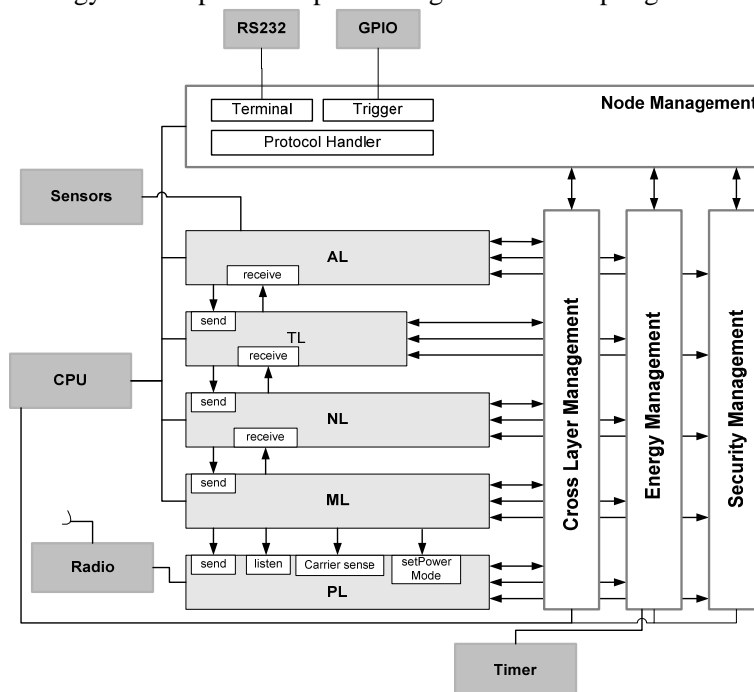

Figure 1: Protocol architecture for wireless sensor networks with partial hardware mapping

The CLAMP communicates with all the layers of the protocol stack, with the energy and security management plane, and with the node management plane allowing every individual component of the system to fully exploit the benefits from information available across all layers.

A) CLAMP ARCHITECTURE

The CLAMP architecture (Fig. 2) comprises three components: a database, services and a set of interfaces. The database is basically a collection of well-defined performance aware and energy aware network parameters and is implemented as a simple list.
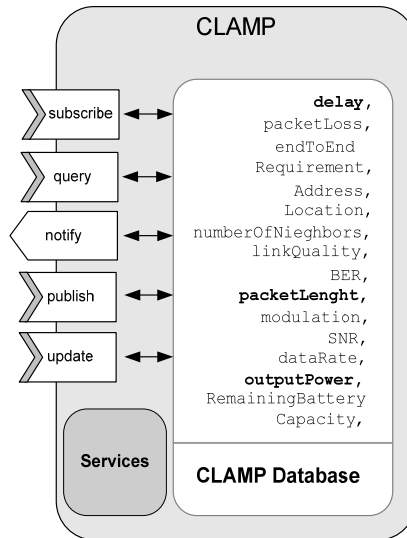

Figure 2: CLAMP Architecture

The interfaces are offered to all other modules of the sensor node to publish, query and subscribe to parameters. The service component keeps record of the modules which have subscribed to certain parameters and notifies them. The main emphasis is given to the fact that the architecture should be accommodated in least possible amount of memory and its processing overheads should not counter-act the benefits which cross layer design can offer to wireless sensor networks.

B) CLAMP DATABASE

We define a list of parameters kept by the CLAMP database with their meaning, the owner, the type, and the valid range. The list is non exhaustive and we are still in process of refining these parameters. But what we argue is that it should contain a list of well-defined parameters instead of implementing a service discovery (here: parameter discovery). The latter would result in processing overheads which is avoided by our approach and facilitates the plug and play feature to a great extent. The list of network parameters and their potential use is given in Table 1.

TABLE 1: CLAMP parameters; profile and potential use

Delay:

Owner: Application Layer (AL)

Description: Delay tolerance defined by the Application Layer. 0 % would mean real time application with strict end to end delay requirements. 100% means that there are absolutely no delay requirements.

Potential Use: The AL defines the delay tolerance and the Routing Layer (RL) may act accordingly, keeping in view e.g. the remaining battery capacity or any other potential parameter. In case of minimum delay tolerance, the RL may decide to use minimum hop routes or less congested routes instead of minimum cost routes to send the information within time restrictions at the cost of more

energy consumption.

packetLoss:

Owner: Application Layer (AL)

Description: Packet Loss Tolerance defined by AL.

Potential Use: The AL may set it to notify other layers, regarding its packet loss tolerance and the RL or Mac Layer (ML) can avoid acknowledgment messages, or retransmissions to save some energy.

Additional Considerations: A low value of packetLoss may require a Transport layer for end to end reliability and also initiates the need of acknowledged services.

Address:

Owner: Routing Layer (RL)

Description: Logical address set by the RL.

Potential Use: The own address is written to this field and can be used by different layers, e.g. if a wakeup radio is used, and it is woken up by a wake-up signal including the address of the node, so it can decide what to do. The address may change from time to time depending upon RL requirements and hence included here.

Location:

Owner: RL

Description: The location of the node. The location is defined by the longitude and latitude and elevation for some specific location e.g. <03'37"55, 56'13"23, 837m>

Potential Use: The reference or global location information is provided by RL and can be used by different layers, e.g. AL may decide that it has already enough information regarding the required phenomenon in a specific location and it does not need this information from a group of nodes for some time (defining area dominating set [9]). So this group of nodes can go to sleep to save energy. Location can also be very helpful to geographic aware routing [10].

noOfNeighbors :

Owner: RL

Description: Number of neighbors of a node.

Potential Use: This information may be utilized by the ML for synchronization purposes or adaptive division of time slots for accessing the medium.

linkQuality:

Owner: MAC Layer (ML)

Description: Link quality provided by the ML.

Potential Use: For high link quality PL can increase the data rate to exploit the opportunity or it may decrease the transmit power to save energy.

BER:

Owner: ML

Description: bit error ratio, calculated by -10*log10(BER), so 40 means 10-4, 70 means BER = 10^{-7}

Potential Use: Depending upon BER, the PL can increase the output power or it can be compared with packet loss tolerance of the AL and decide what to do.

Additional Consideration: A calculation model of the BER is not provided here. A receiver could estimate the BER (and/or SNR) from a received packet and its count of bit errors. In WSNs this is a major computation effort and therefore usually not provided.

packetLenght:

Owner: ML
Description: Length of the transmit packet defined by ML.
Potential Use: The packet length can effect output power and bit error rate [11]. Short packet sizes results in inefficient energy usage because of large overheads while long packet sizes may experience higher number of errors, so energy efficiency can be maximized by optimal packet size [12]. If packet reception probabilities are used instead of transmission radius for communicating with neighbors, it can be calculated based on bit error ratio and packet length [12].
Additional Consideration: Here we talk about the Packet Length which is actually transmitted over the physical medium as this length is the one which affects different network variables.

Modulation:

Owner: Physical Layer (PL)
Description: Digital modulation technique utilized by the main transceiver.
Potential Use: The modulation at PL can be changed depending upon the remaining capacity of the battery [11]. The number of packets in the system (in buffer or queue or being in transmission) can affect the constellation size of the modulation scheme [13].

SNR: Signal to Noise Ratio defined by PL

Owner: PL
Description: Signal to noise ratio of the received packet expressed in dB.
Potential Use: If the SNR is low and AL has provision of delay tolerance, and the battery capacity is also low, than it can be decided to back off for some time and complete communication later on or otherwise output power can be increased.
Additional Consideration: Usually a transceiver offers an RSSI value but you can't measure the noise level. Therefore the SNR value will not be provided by most implementations.

dataRate: Data rate defined by PL

Owner: PL
Description: Data rate in kilobytes per second.
Potential Use: The lifetime of the network can be extended by using varying data rate at each node in the routing path. Reducing transmission rates at critical nodes (energy constrained) also results in extended network life time [14]. If data rate is increased, the probability of encountering errors also increases, so a higher output power is required to have an acceptable SNR and thus BER at the receiver. [15].Based on the data rate requirements, the modulation scheme can be selected [15].

outputPower: Transmit power defined by PL

Owner: PL
Description: transmit power of the radio given in dBm.
Potential Use: The modulation scheme, with certain BER threshold values and SNR can be used to calculate the transmit power [15]. The optimal transmit power increases with increase in the data rate (vulnerable time is decreased but thermal noise is also increased) [16]. A carefully chosen data rate can have high impact on transmit power and network life time [16].

remainingBatteryCapacity: defined by EMP

Owner: Energy Management Plane (EMP)
Description: Remaining batter capacity in mWs, i.e. a value of 100 means there are 100mWs. Full scale value means that remaining capacity is more than the value can represent.
Potential Use: If the remaining capacity is at some threshold, than the node can back-off for some time, to allow the battery to recover and than take part in communication. It can also be helpful in case of

energy aware routing protocols like EADV [17] or Mac protocols like CSMA-MPS [20] where the wakeup frequency could be adjusted based on the amount of available energy.

Additional Consideration: Calculating this value is difficult because the voltage characteristic (commonly used to calculate the capacity) of accumulators doesn't offer good estimations. From this value a decision should be done whether we continue to send packets or we send a "I go to sleep" packet. The resolution for such a value should fit for large batteries (10Ah) down to capacitors (1F). Therefore a value giving the relative capacity of the battery (0-100%) would be better suited.

C) CLAMP INTERFACES

The interfaces are *publish*, *update*, *subscribe*, and *query*. Initially the CLAMP database is empty. Every module can publish its parameters and thus is their owner. Later on it can update the value of a particular parameter. All other modules can query the current value of a parameter. Additionally they can subscribe to parameters. Once there is a change in any of the values of the known parameters, The CLAMP notifies all the subscribed modules with the help of the notify call. If any layer subscribes to a parameter which has not (yet) been published, the services module keeps track of the client and notifies it as soon as that particular parameter is published. The query interface is provided in case a particular module does not need to be notified every time there is a change in a value.
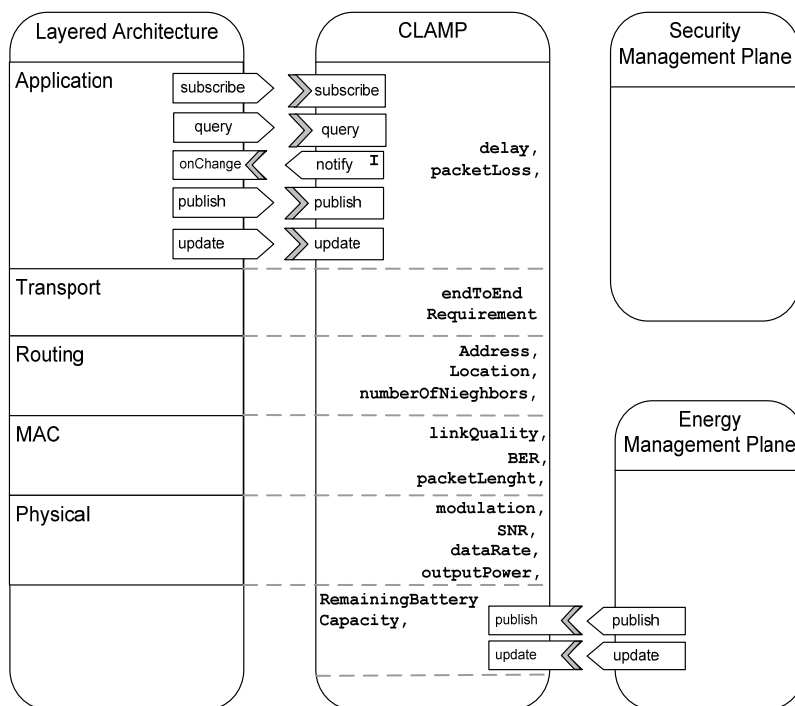

Figure 3: Interfaces between CLAMP and other modules

IV.   IMPLEMENTATION DETAILS

The architecture is currently implemented in the PAWiS framework for modeling and simulation of wireless sensor networks as part of the PAWiS project [18]. This uses C++ classes to model the node modules and uses so called functional interfaces to model interfaces (i.e. remote procedure calls) between modules. These functional interfaces are utilized to implement the communications between the network layers as well as to the CLAMP and other planes. Every invocation is managed by the discrete event

simulation environment utilizing a future event list and a lot of overhead to deliver messages between the various modules. The descriptions in the preceding sections assume the usage of the PAWiS framework rather than a firmware implementation of a particular sensor node.

In the firmware different techniques have to be utilized for interfaces and parameters to reduce complexity and overhead. All interfaces should be implemented as regular function calls. CLAMP parameters which are only queried without modules which need immediate notification of changes should be implemented as global variables. For CLAMP parameters with subscribed modules another approach is necessary e.g. call back function calls. In sensor nodes with real time operating system like tinyOS [22], the architecture can be implemented in more or less the same way as in simulation framework.

V. PRELIMINARY RESULTS

Currently we have simulated the concept in the PAWiS [18] framework. The current simulation results show that the concept is computationally feasible and can be beneficial for low power wireless sensor networks. As an example, we implemented a non-linear remaining battery calculating algorithm [19] in the energy management plane, which updates the approximate remaining battery capacity within the CLAMP database. This remaining battery capacity can now be used by the AL to back off for some time so that the battery can undergo the recovery effect. Fig. 4 shows the graph of the remaining battery capacity against time for three different nodes. This information can be very useful in many aspects if a particular node knows about the battery level of itself and the battery level of its neighbors for routing decisions in energy aware routing protocols. Node 3 has higher battery level than node 1 and node 2 because in the simulated topology, node 3 only generated the self traffic and didn't relay any data packets. Figure 4 depicts the normalized battery value of only 3 nodes.
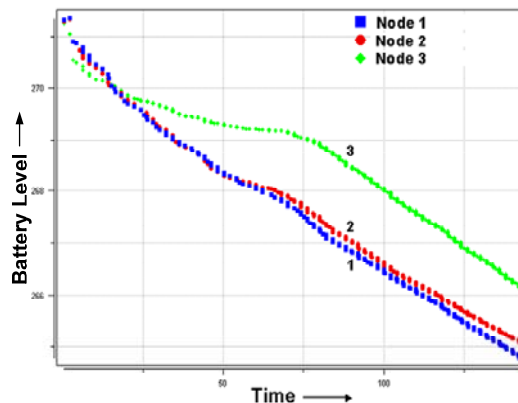

Figure 4: Remaining battery capacity information provided to CLAMP by energy management plane.

The remaining battery capacity provided to the routing layer resulted in extended network life time. We simulated the sensor nodes distributed randomly based on uniform distributed in an area of 200 x 200 m2. The batteries were initialized with unrealistic limited amount of energy without loss of generality to reduce the simulation run time. Figure 5 clearly shows that the routing based on remaining battery capacity [17] has extended network life time as compared to the routing based on progress (minimizing the distance towards the fusion center in position based routing schemes) towards the sink node. Both the curves show a downward trend with increasing number of nodes. This is due to the increasing chances of collisions and hence retransmission at a higher density of nodes. Network life time is considered to be the exhaustion of the first node in the networks.
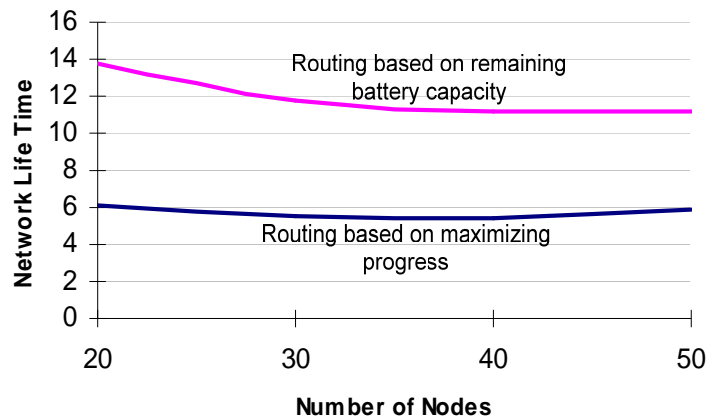
Figure 5: Effect of remaining energy aware routing on network life time

Figure 6 shows the remaining energy of each node at the end of the simulation time. It is clear from the figure that those nodes running remaining-battery-energy aware routing protocol has higher energy values than those running progress aware routing protocol. The two nodes encircled in red show that almost the same amount of remaining energy, because these nodes only generates self traffic and does not take part in relaying data because of their topological location. The set of available parameters make it possible even to change the behavior of routing schemes at run time. For instance, in environmental application, with periodic sampling of data, the routing decisions can always be taken on the basis of remaining energy to extend the network life time. But incase of an unusual event, like reported temperature is beyond certain upper threshold, routing decisions can be based on delay aware metrics.
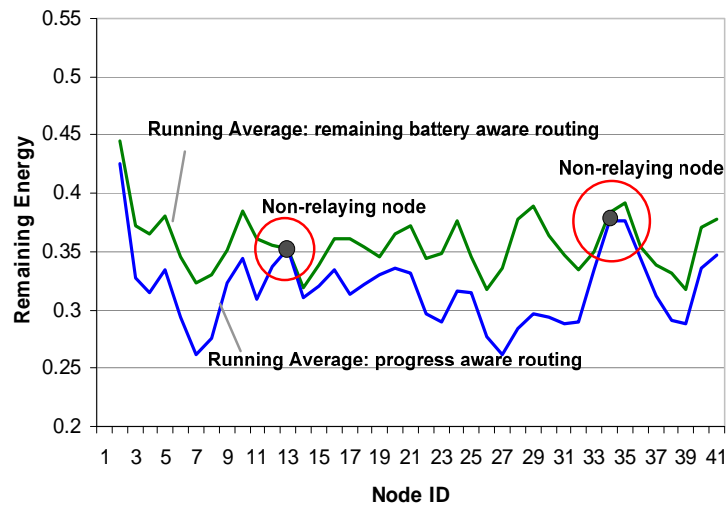

Figure 5: Remaining energy of individual nodes after simulation run time

VI.   CONCLUSION

In this paper we presented an architecture for a cross layer management plane as a part of a protocol architecture for low power wireless sensor networks. We have already simulated the architecture and have

shown that the concept is computationally feasible and is beneficial. We have not yet realized the proposed scheme on real wireless sensor node platform as we are in a process of fine tuning the parameters to be provided by the CLAMP database for cross layer optimization benefits. A distributed algorithm, which utilizes the cross layer information and provides input to different layers in a standardized way, is a challenging problem. We intend to implement this architecture on the real node (tinyMote [23] developed at our institute) as part of the PAWiS [18] project funded in part by the Austrian Research Program FIT-IT and with Infineon as industry partner.

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