Simulation Study on Cross-Layer Design for Energy Conservation in Underwater Acoustic Networks*

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***Abstract* – As the underwater part of a heterogeneous system which integrates underwater, terrestrial radio and satellite communications in a resilient infrastructure, underwater acoustic network will play an important role. It serves for the underwater information acquisition and transmission. Supported by efficient underwater acoustic communications, the networking would focus on the construction of the network which will ensure efficient operation. In underwater acoustic sensor networks, energy consumption is a critical problem to be considered. It is not a simple problem of power source supply, while it is a synthetic result of power management, protocol planning, etc. Therefore, the solution should be an integrated scheme to combine several aspects during networking. Cross-layer design could contribute to this objective. In this paper, a fusion about MAC and Routing protocols, as well as the topology design, is studied in order to gain more profits for networking. The simulation shows its efficiency.**

Keywords: underwater acoustic sensor networks, cross-layer design, energy conservation

I. Introduction

With the increasing demand of resource finding in the oceans, many projects have been carried out. There is a trend to combine various networks into one comprehensive system to supply various information. Among them, CAMOS (Coastal and Arctic Maritime Operations and Surveillance sensor networks) is a cross-disciplinary project whose primary objective is to develop a robust integrated communication framework that integrates underwater, terrestrial radio and satellite communications in a resilient infrastructure that can support a multitude of applications, primarily within sensor networking in the Arctic region.

Underwater Acoustic Networks (UAN) will play an important role in the CAMOS. It serves as the underwater part of the heterogeneous system, in charge of the underwater information acquisition and transmission. Based on efficient underwater acoustic communications, the networking would focus on two aspects: one is the construction of the network, including the designation of protocols, which will ensure efficient operation; the other is the guarantee of the safety and security of the network, which will ensure its normal operation. This paper will focus on the first part of the networking, especially on the design of protocols. In underwater acoustic networks, energy consumption is a critical issue to be considered. This issue does not only involve power source supply, but also it is a synthetic result of power management and protocol planning. Therefore, the solutions should be an integrated scheme to combine several aspects during networking. While most of the research on underwater networking so far has followed the traditional layered approach for network design, it is an increasingly accepted opinion that the improved network efficiency, especially in critical environments, can be obtained with a cross-layer design approach [1]. This paper will consider this viewpoint, trying to do some fusion work about MAC and Routing protocols, as well as the topology design, in order to gain more profits for CAMOS application.

II. General Layering of Underwater Acoustic Networks

The well-known ISO-OSI 7-layer hierarchical structure is the first standard on network layering, which explicitly presents the functionality of each layer. But it is not so practical. Therefore many other standards are being used in different kinds of networks. For instance, TCP (UDP) / IP is widely-used in the Internet, which has been the standard in fact [2].

A. General Layering of UAN

Though there is a possibility for ubiquitous underwater acoustic networks [3], the current status of UAN development is still with various standards of individual developers. Generally, UAN includes 5 layers, which is shown in Figure 1 [1].

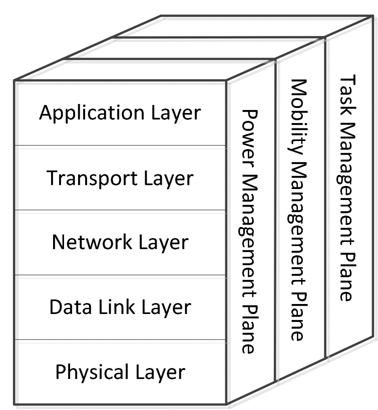

Fig. 1. Illustration of UAN General Layering

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It can be said that this is the protocol stack of general UAN. It combines power and routing awareness, integrates data with networking protocols, communicates power efficiently through the wireless medium, and promotes cooperative efforts of sensor nodes. The protocol stack consists of 5 layers, which are related to 3 planes.

Power Management Plane manages how a sensor node uses its power; Mobility Management Plane detects and registers the movement of sensor nodes (for mobile UAN); and Task Management Plane balances and schedules the sensing tasks given to specific region.

These management planes are needed so that sensor nodes can work together in a power efficient way, and share resources between sensor nodes.

B. MAC and Routing in UAN

1) Multiple Access Control

Multiple Access Control (MAC) is one of the distinguished characteristics of networks compared with point-point communications, whose objective is to prevent collisions in the access channel, thus maximizing the network efficiency. MAC is the main function of Data Link Layer.

In UAN, it will pose additional challenges due to the peculiarities of the underwater channel, in particular limited bandwidth, high and variable delay. Therefore, contention-based methods like MACA [4] are not suitable for UAN. To take advantage of those pre-allocating protocols such as FDMA, TDMA and CDMA [5], various modifications must be pursued to meet various underwater conditions and applications.

2) Routing

Routing is the major task in Network Layer, which is in charge of determining the path between a source and a destination node. As a total, network routing protocol gives a rule for all connections.

In the existing study, there are mainly two categories: *Proactive protocols* - attempt to minimize the message latency induced by route discovery, by maintaining up-to-date routing information at all times from each node to every other node, such as DSDV [6] and OLSR [7]; *Reactive protocols* - initiate a route discovery process only when a route to a destination is required. Once a route has been established, it is maintained by a route maintenance procedure until it is no longer desired, such as AODV [8] and DSR [9].

III. Cross-Layer Design

One of the critical limitations of UAN's application is its power supply. Battery power is limited and usually batteries cannot be recharged, also because transformation from other energy like sea current is still not practical.

So far we have introduced the general layering of UAN, and presented some basic knowledge of MAC and routing peculiarly. Considering of the network topology, in this paper, we propose a solution for energy conservation within UAN.

A. UAN Topologies

From its original development, UAN has been used as underwater information collection and transmission. Unlike the Internet in which each user could be the terminal (thus it is a peer to peer network), UANs generally are with a centralized topology. That is to say, all of the data streams would converge to one sink before going out of water.

Figure 2 presents a simplified topology of UAN.

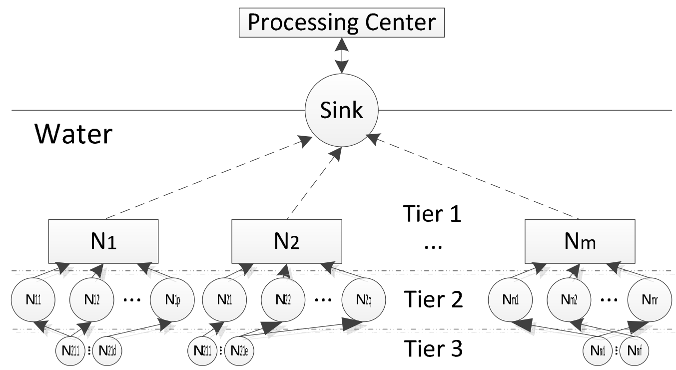

Fig. 2. A Simplified Illustration of UAN Topology

In the figure, *Sink* is the gateway for information from/to water; *Processing Center* is the user of collected information; $N_{x(xx)(xxx)}$ are underwater nodes which belong to different tiers. According to various applications, the structures of UAN may vary significantly. The figure gives an example of a 3-tier network with certain topologies.

B. Energy Consumption Model

Almost every action in the network would consume the battery energy, such as MAC, routing, network management, and task distribution. Fundamentally, we should say that energy consumption occurs when there is signal sending or receiving by a node to/from another, as well as the pre- and post-processing. Compared to the situation discussed above, other consumptions could be ignored.

1) Transmission Power

In sonar equations, *SL* (Source Level) is related to transmission power. It can be represented as [10]

$$SL = 10\log\frac{I_t}{1\mu Pa} \tag{1}$$

where I_t (in μPa) is sound intensity and is equal to

$$I_t = 10^{\log SL/10} \times 0.67 \times 10^{-18}\ (W/m^2) \tag{2}$$

The transmission power P_t can be calculated by

$$P_t = 2\pi \times 1m \times H \times I_t\ (\mathrm{W}) \tag{3}$$

where H is the depth of the underwater transmitter.

2) Node Power Consumption

Taking a general condition into account: one node sends data to the other, and receives data from another node, and acknowledge is needed.

Assume a normalized model for power consumption. Let the transmission power be 1W and the receiving power be 1/5 of the transmission power; let the acknowledge transmission consumption be 1/5W and receiving acknowledge need be 1/25W. Thus we get the node power consumption

$$P_n = R \times P_t \times M\left(1 + \frac{1}{5} + \frac{1}{5} + \frac{1}{25}\right)\text{(W)} \quad (4)$$

where M is the number of data packets that the node forwards during an update period, R is the average times for successfully sending a packet.

Considering there is a certain probability (say p) for a successful transmission, R can be calculated by

$$R = 1/p^2 \quad (5)$$

3) Network Power Consumption

Suppose the network with M nodes and each node is with the power consumption of (4). Thus we can get the overall power consumption of the network:

$$P_N = \sum_{n=1}^{M} P_n \quad (6)$$

It should be noticed that the power consumption for each node is not the same. Therefore, P_N is based on the statistics of nodes' behaviors.

C. Cross-Layer Design for Energy Conservation

1) Generic Design Based on Layering

Layering to networks makes it explicit to protocol design. Figure 3 presents the generic design corresponding to the 5-layer model of UAN shown in Figure 1 [11].

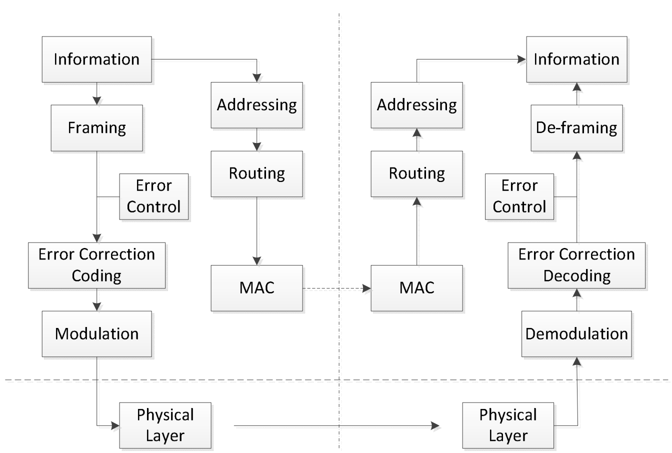

Fig. 3. Generic Design of UAN Protocols

Layering Design has obtained great successes in wire-based networks. The Internet is one of the successful examples. But in UAN, due to the frequent collisions, inter-user interferences and signal attenuations, it brings two problems: non-Optimal, and non-Flexible [12].

Non-Optimal is because the individual design in each layer lacks information sharing, resulting that information is insufficient for each layer. This cannot bring integral optimization to the whole network; Since Layering Design demands that the network should work properly even under the worst circumstances, it can only be designed based on the worst conditions. Thus the design lacks adaptive capability to environment varying, which shows non-Flexible [13].

In this paper, we call this design LD (Layering Design), which will be used for comparisons later.

2) Cross-Layer Design

To counter the two shortcomings, Cross-Layer Design comes up in recent years, especially in the territorial wireless networks. The main thinking is to break the traditional layering concept by taking the whole network as a whole in the design, analysis and control, in order to get optimal and flexible protocols. A scheme of Cross-Layer Design has been proposed by Pompili, etc. [14]

Figure 4 presents a concrete implementation of Cross-Layer Design.

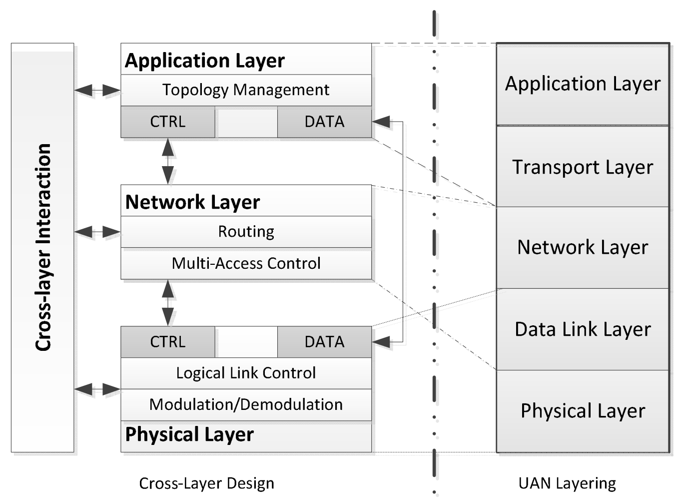

Fig. 4. A Concrete Implementation of Cross-Layer Design for UAN

We can call this design as CLD, which is just the short of Cross-Layer Design.

3) Features of the Cross-Layer Design

From Figure 4, we can draw some conclusions of the proposed Cross-Layer Design as follows.

Firstly, the layers are re-organized. Corresponding to the 5-Layer model, the new design is reduced to 3 layers – Application Layer, Network Layer and Physical Layer.

- *Physical Layer*: Unites Physical Layer and part of Data Link Layer (LLC), whose missions include Logical Link Control and physical transformation.
- *Network Layer*: Joints Network Layer and part of Data Link Layer (MAC), in charge of routing and multi-access control.
- *Application Layer*: Combines the functions of Transport Layer, pursuing Topology Management.

Secondly, a new middleware called *Cross-layer Interaction* is added to implement the information sharing between layers and meet the demands of cross-layer applications.

Thirdly, different from the 5-layer model, the information transferred between layers is divided into two classes: CTRL standing for control information; and DATA for user data. CTRL adopts the normal passing mode; while DATA passes directly between Physical and Application Layer, ignoring Network Layer.

4) Energy Conservation Analysis

Cross-Layer Design brings not only power conservation, but also other benefits for the network, such as larger throughputs, less end-to-end delays. In this paper, we only discuss the profits achieved for power conservation.

As analyzed above in part *B* of this section, most of energy are consumed when there is information exchange between nodes.

There are two aspects to be considered:

- *Transmitting and receiving signals*: These two circumstances are bond to occur in a network. To conserve the energy consumption, the node should reduce the occurrences of transmission or transmit with lower power.
- *Pre- and post-processing*: Before transmission, the formation of the signal is with several steps, including addressing, framing, coding and modulation, etc.; While after receiving, the reverse procedure would occur. To conserve energy consumption, the procedures should be made more compact.

In CLD, we have taken some measures corresponding to the two aspects discussed above:

- For transmissions between nodes, the new Network Layer with MAC procedure reduces the RTS/CTS times; the new Physical Layer pursues the error control (within LLC) and brings more precision, so that NAK (Negative Acknowledgement) signals are reduced greatly.
- Inside a node, under the management of the Cross-Layer Interaction, CTRL and DATA from/to the Physical Layer are individual. Thus, CTRL could retain the same, and DATA passing is only between the Application and Physical Layer. So the internal information transmissions are reduced as well.

IV. SIMULATIONS AND ANALYSIS

In this section, we will present some simulations to verify the capability of energy conservation with Cross-Layer Design.

A. Simulation Scenario

1) Network Model

Figure 5 shows the topology of the target network.

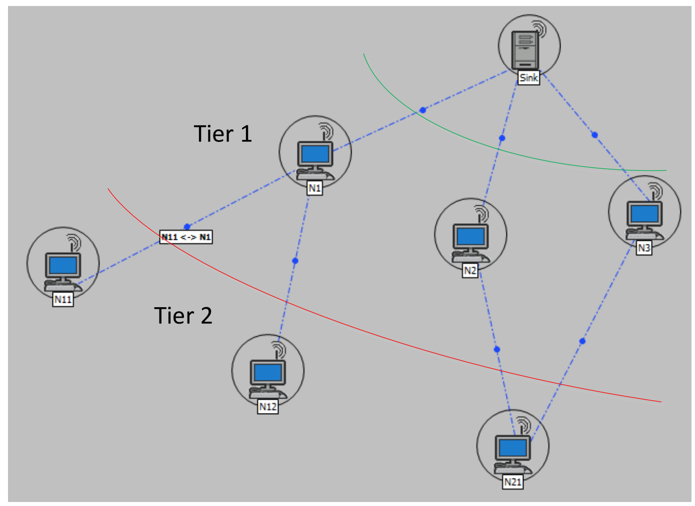

Fig. 5. Simulation Senario of UAN

Using Opnet, WLAN (wireless LAN) models are borrowed as underwater acoustic network nodes with relative modification to imitate the situations of undersea environment.

To give fair comparisons, the same UAN topology is used in the simulations.

It is with a hybrid infrastructure: *Sink* is the central node; Both Tier 1 and Tier 2 has 3 nodes; N11 and N12 both go to N1, and N21 can go to either N2 or N3.

2) MAC and Routing Protocols

A modified CDMA [5] is used as MAC protocol, and a modified AODV [15] is adopted as routing protocol in the simulations.

3) Communication Parameters

CTRL and DATA parameters are the same as those of Table 2 in [13].

B. Energy Consumption Comparisons

In Figure 5, the interval of each lower tier node sending information to upper ones is set to 20 minutes and the results of energy consumption in simulations are normalized.

Equations (4) and (6) are used for the calculations of the power consumption.

Figure 6 shows the energy consumption comparisons (averages of 100 simulations) of LD and CLD according to the scenario mentioned above.

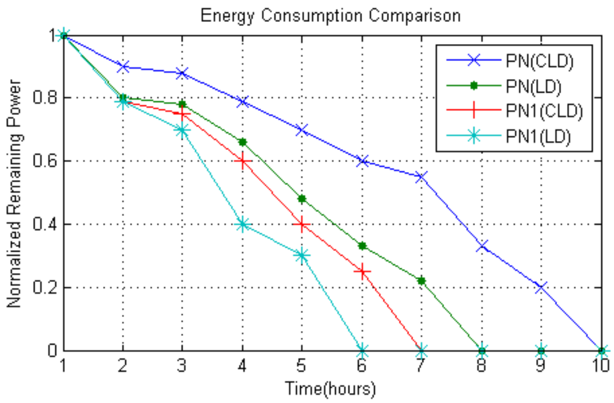

Fig. 6. Remaining Power Comparison. Upper 2 lines are normalized energy consumpions of the entire network, Lower 2 lines are those of node N1 (in Fig. 5).

Figure 6 gives two pairs of comparison: P_N is the normalized remaining power of the total network; P_{N1} is that of node N1. It can be seen that the power consumption of CLD is less than that of LD, both for the network and the nodes.

V. SUMMARY

There is a trend to use heterogeneous network system in resource exploration. Among those projects, CAMOS is an ambitious one, where UAN will play an important role.

One of the critical problems of UAN is its power supply. Different protocols would bring various properties of power consumption. After studying the power consumption model, we proposed a cross-layer design method for energy conservation structure. The design reduces signal exchanges between nodes, as well as the information passing inside of the nodes.

Simulations show that the Cross-Layer Design is successful in energy conservation, both in the network scale and the node levels.

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