Review on Under Water Sensor Networks

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Abstract: Underwater sensor networks (UWSNs) are becoming popular everyday due to their ability which makes them to be deployed under adverse environmental conditions. UWNs are the enabling technology for a wide range of applications like pollution monitoring, nutrient production, oil retrieval and transportation. The use of acoustic communication underwater environment posses many interesting challenges. Because of high transmission power, energy consumption is more, making medium access protocol a primary focus point for reducing energy consumption. However sensed data can be interpreted meaningfully when referenced to the location of the sensor, making localization an important problem. In this chapter, we give a survey on the architectural view and the protocols used for underwater sensor networks.

2.1 Overview

The following chapter throws light on the theoretical background that is required in studying the different ways in which the current problem has been dealt with in the past. It goes on to give a brief outline of the various protocols that have been used in the existing system, the architectures that are used. Finally deals with ideas which are most related to the proposed project.

2.2 Underwater sensor networks

Underwater sensor networks are envisioned to enable applications for oceanographic data collection, pollution monitoring, offshore exploration, disaster prevention, assisted navigation and tactical surveillance applications. Multiple unmanned or autonomous underwater vehicles (UUVs, AUVs), equipped with underwater sensors, will also find application in exploration of natural undersea resources and gathering of scientific data in collaborative monitoring missions. To make these applications viable, there is a need to enable underwater communications among underwater devices. Underwater sensor nodes and vehicles must possess self-configuration capabilities, i.e., they must be able to coordinate their operations by exchanging configuration, location and movement information, and to relay monitored data to an onshore station.

Underwater sensor networks (USNs) consist of a variable number of sensors designed to collaboratively monitor an oceanic environment. To achieve this objective, sensors self organizes into an autonomous network that can adapt to the characteristics of a given underwater area. The main motivations for USNs are their relative ease of deployment and lower costs, as they eliminate the need for underwater cabling and do not interfere with shipping activities. In underwater environments, radio does not work well due to its quick attenuation in water.

Thus, acoustic channels are usually employed. Underwater acoustic channels are characterized by long propagation delays, limited bandwidth, motion-induced Doppler shift, phase and amplitude fluctuations, multipath interference, etc. [1].
These characteristics pose severe challenges towards designing localization schemes that fulfill the following desirable properties:

High Accuracy
The location of the sensor for which sensed data is derived should be accurate and unambiguous for meaningful interpretation of data. A localization protocol usually minimizes the distance between the estimated and true locations.

Fast Convergence
Since nodes may drift due to water currents, the localization procedure should be fast so that it reports the actual location when the data is sensed.

Wide Coverage
The localization scheme should ensure that most of the nodes in the network can be localized.

Low Communication Costs
Since the nodes are battery-powered and may be deployed for long durations, communication overhead should be minimized.

Good Scalability

The long propagation delay and relatively high power attenuation in the underwater acoustic channel pose a scalability problem where performance is highly affected by the number of nodes in the network. Consequently, an underwater acoustic localization protocol should be distributed and rely on as few reference nodes as possible [2].

2.3 Underwater network operating regimes

Underwater networks can be characterized by their spatial coverage and by the density of nodes. These factors have significant implications for the MAC- and network-layer issues that must be addressed at design time. Taxonomy of underwater network operating regimes is illustrated in Fig. 2.1. We characterize the spatial extent of a network by comparing it to the acoustic range of the nodes. If all nodes are in direct contact, we have a single-hop network, with either centralized or distributed control. In networks covering larger areas, communications will require multiple hops to reach destinations. When the geographic coverage is greater than the un- partitioned link-layer coverage of all nodes, routing requires techniques from disruption-tolerant networking (DTN). When even the mobility of nodes does not overlap, no techniques exist to form a network.
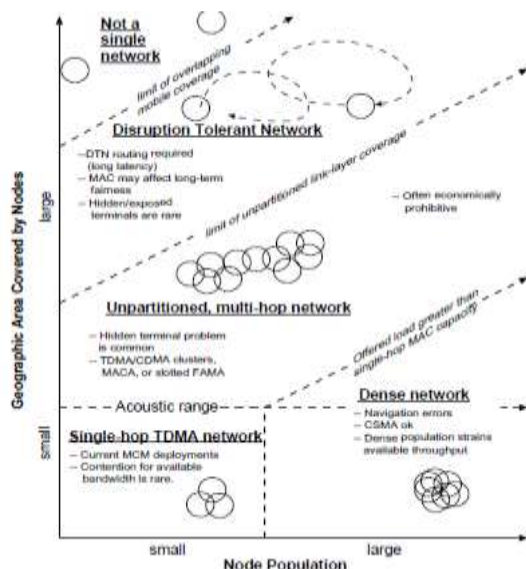

Fig. 2.1: Taxonomy of underwater network

operating regimes.

There are several additional differences of note between terrestrial radio-based networks and underwater acoustic sensor networks. One is that large populations of nodes in small areas can cause conflicts with throughput and navigation. A second point is that densely populating a large geographic area can be simply prohibitively expensive. In practice, all of the network types shown in Fig. 2.1 are relevant and can exist within an extended network. In other words, clusters of single- or multi-hop networks can be deployed that use DTN routing to exchange information infrequently [2].

2.4 UNDERWATER NETWORK ENVIRONMENT

A sample underwater (UW) network environment is as shown in the Fig. 2.2. The network consists of a set of underwater local area networks (UW-LAN, also known as clusters or cells). Each sensor is connected to the sink within the cluster. The sensors can be connected to uw-sinks via direct paths at multiple hops.
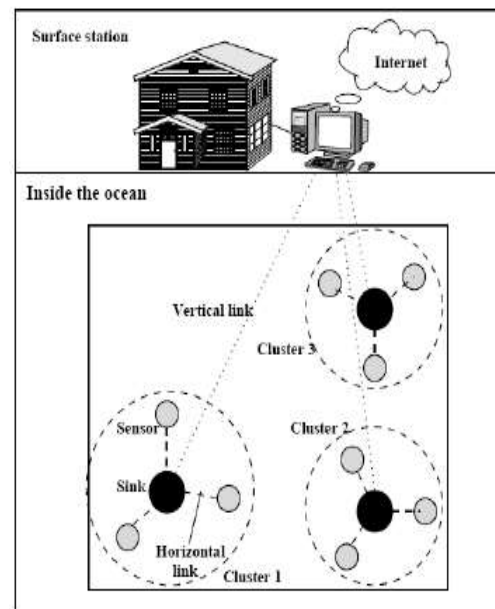

Fig. 2.2: Underwater network environment

The information from the sink of each cluster transfers to surface station through vertical links. The station at the surface is equipped with acoustic transceivers that are capable of handling multiple parallel communications with the deployed UW-sinks [3].

2.5 Underwater network architecture

The network topology is in general a crucial factor in determining the energy consumption, the capacity and the reliability of a network. Hence, the network topology should be carefully engineered and post deployment topology optimization should be performed, when possible.

Underwater monitoring missions can be extremely expensive due to the high cost of underwater devices. Hence, it is important that the deployed network be highly reliable, so as to avoid failure of monitoring missions due to failure of single or multiple devices. For example, it is crucial to avoid designing the network topology with single points of failure that could compromise the overall functioning of the network.

There are three different underwater acoustic sensor architectures which are as follows:

Static two-dimensional UW-ASNs
For ocean bottom monitoring, these are constituted by sensor nodes that are anchored to the bottom of the ocean. Typical applications may be environmental monitoring, or monitoring of underwater plates in tectonics.

Static three-dimensional UW-ASNs
For ocean column monitoring, these include networks of sensors whose depth can be controlled by means of techniques, and may be used for surveillance applications or monitoring of ocean phenomena (ocean bio–geochemical processes, water streams, pollution).

Three-dimensional networks of autonomous underwater vehicles (AUVs)
These networks include fixed portions composed of anchored sensors and mobile portions constituted by autonomous vehicles [4].

2.5.1 Two-Dimensional Underwater Sensor Networks

Reference architecture for two-dimensional underwater networks is shown in Fig. 2.3. A group of sensor nodes are anchored to the bottom of the ocean with deep ocean anchors. Underwater sensor nodes are interconnected to one or more underwater sinks (uw-sinks) by means of wireless acoustic links. Uw-sinks, as shown in Fig. 2.3, are network devices in charge of relaying data from the ocean bottom network to a surface station.

To achieve this objective, uw-sinks are equipped with two acoustic transceivers, namely a vertical and a horizontal transceiver. The horizontal transceiver is used by the uw-sink to communicate with the sensor nodes in order to:

- Send commands and configuration data to the sensors (uw-sink to sensors).
- Collect monitored data (sensors to uw-sink).

The vertical link is used by the uw-sinks to relay data to a surface station. In deep water applications, vertical transceivers must be long range transceivers as the ocean can be as deep as 10 km. The surface station is equipped with an acoustic transceiver that is able to handle multiple parallel communications with the deployed uw-sinks. It is also endowed with a long range RF and/or satellite transmitter to communicate with the onshore sink (os-sink) and/or to a surface sink (s-sink). Sensors can be connected to uw-sinks via direct links or through multi-hop paths. In the former case, each sensor directly sends the gathered data to the selected uw-sink.

However, in UW-ASNs, the power necessary to transmit may decay with powers greater than two of the distances and the uw-sink may be far from the sensor node. Consequently, although direct link connection is the simplest way to network sensors, it may not be the most energy efficient solution. Furthermore, direct links are very likely to reduce the network throughput because of increased acoustic interference due to high transmission power. In case of multi-hop paths, as in terrestrial sensor networks, the data produced by a source sensor is relayed by intermediate sensors until it reaches the uw-sink. This may result in energy savings and increased network capacity, but increases the complexity of the routing functionality [4].
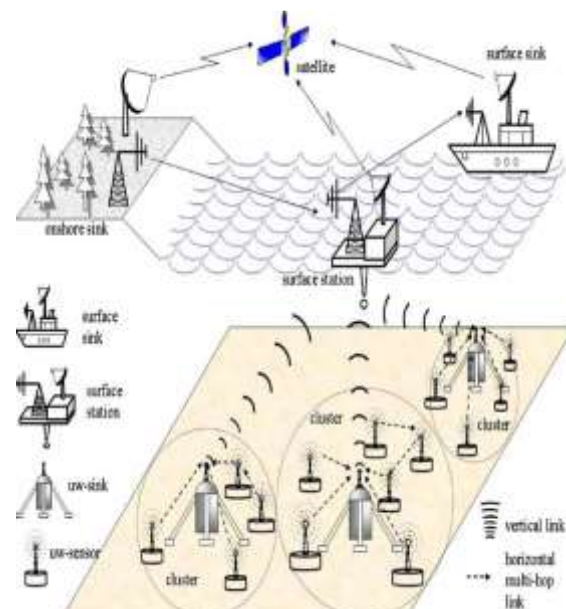

Fig. 2.3: Architecture for 2D underwater sensor networks

The main challenges that arise with two-dimensional architecture are:

⬜ Determining the minimum number of sensors and uw-gateways that need to be deployed to achieve the target sensing and communication coverage, which are dictated by the application requirements.

⬜ Providing guidelines on how to choose the optimal deployment surface area, given a target bottom area

⬜ Studying the topology robustness of the sensor network to node failures, and provide an estimate of the number of redundant sensor nodes to be deployed to compensate for failures [2].

2.5.2 Three-dimensional Underwater Sensor Networks

In three-dimensional underwater networks, sensor nodes float at different depths in order to observe a given phenomenon. One possible solution would be to attach each uw-sensor node to a surface buoy, by means of wires whose length can be regulated so as to adjust the depth of each sensor node.

However, although this solution allows easy and quick deployment of the sensor network, multiple floating buoys may obstruct ships navigating on the surface, or they can be easily detected and deactivated by enemies in military settings. Furthermore, floating buoys are vulnerable to weather and tampering or pilfering. For these reasons, a different approach can be to anchor sensor devices to the bottom of the ocean.

In this architecture, depicted in Fig. 2.4, each sensor is anchored to the ocean bottom and equipped with a floating buoy that can be inflated by a pump. The buoy pushes the sensor towards the ocean surface. The depth of the sensor can then be regulated by adjusting the length of the wire that connects the sensor to the anchor, by means of an electronically controlled engine that resides on the sensor [3].

A challenge to be addressed in such architecture is the effect of ocean currents on the described mechanism to regulate the depth of the sensors.

2.5.3 Sensor Networks with Underwater Vehicles

AUVs can function without tethers, cables, or remote control, and therefore they have a multitude of applications in oceanography, environmental monitoring, and underwater resource study. Previous experimental work has shown the feasibility of relatively inexpensive AUV submarines equipped with multiple underwater

sensors that can reach any depth in the ocean. Hence, they can be used to enhance the capabilities of underwater sensor networks in many ways. The integration and enhancement of fixed sensor networks with AUVs is an almost unexplored research area which requires new network coordination algorithms.
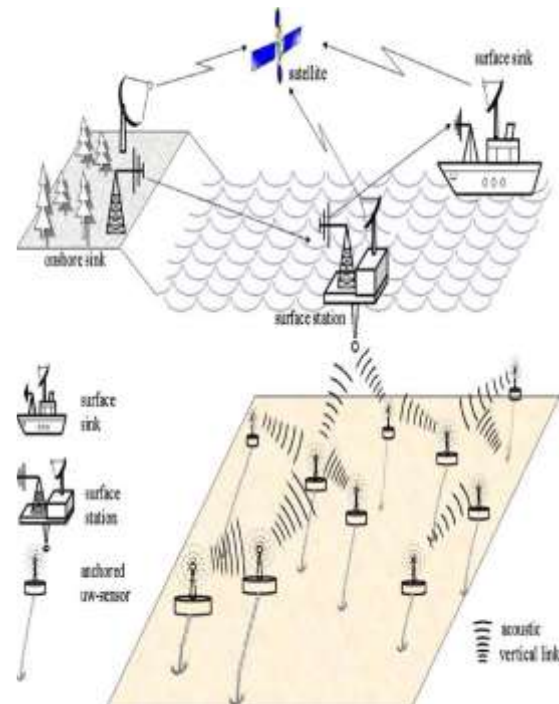

Fig. 2.4: Architecture for 3D underwater sensor networks

One of the design objectives of AUVs is to make them rely on local intelligence and less dependent on communications from online shores. In general, control strategies are needed for autonomous coordination, obstacle avoidance and steering strategies. Solar energy systems allow increasing the lifetime of AUVs, i.e., it is not necessary to recover and recharge the vehicle on a daily basis. Hence, solar powered AUVs can acquire continuous information for periods of time of the order of months.

Several types of AUVs exist as experimental platforms for underwater experiments. Some of them resemble small-scale submarines. Others are simpler devices that do not encompass such sophisticated capabilities. For example, drifters and gliders are oceanographic instruments often used in underwater explorations. Drifter underwater vehicles drift with local current and have the ability to move vertically through the water column. They are used for taking measurements at preset depths. Underwater gliders are battery powered

autonomous underwater vehicles that use hydraulic pumps to vary their volume by a few hundred cubic centimeters in order to generate the buoyancy changes that power their forward gliding [4].

2.6 Characteristics of Underwater Acoustic Networks

The characteristics of underwater acoustic networks are as follows:

Communication media

Underwater communication system involves the transmission of information using any media either acoustic waves, electromagnetic waves or optical waves. Each of the techniques has their own advantages and limitations. Acoustic communication is the most versatile and widely used technique in underwater due to low attenuation in water.

Transmission loss

It consists of attenuation and geometric spreading. The attenuation is mainly provoked by absorption due to conversion of acoustic energy into heat, and increases with distance and frequency. The geometric spreading refers to the spreading of sound energy as a result of the expansion of the wave fronts. It increases with the propagation distance and is independent of frequency.

Noise

It can be classified as man-made noise and ambient noise. The former is mainly caused by machinery noise (pumps, reduction gears, power plants), and shipping activity (hull fouling, animal life on hull, cavitations), while the latter is related to hydrodynamics (movement of water including tides, current, storms, wind, and rain), and to seismic and biological phenomena.

Multipath

Multipath propagation may be responsible for severe degradation of the acoustic communication signal, since it generates Inter Symbol Interference (ISI). The multipath geometry depends on the link configuration. Vertical channels are characterized by little time dispersion, whereas horizontal channels may have long multipath spreads. The extent of the spreading is a strong function of depth and the distance between the transmitter and the receiver.

Doppler spread

The Doppler frequency spread causes degradation in the performance of digital communications. The Doppler spreading generates two effects: a simple frequency translation and a continuous spreading of frequencies, which constitutes a non-shifted signal. While the former is easily compensated at the receiver, the effect of the latter is harder to be compensated for [1].

2.7 Challenges in Underwater Acoustic Networks

Major challenges encountered in the design of underwater acoustic networks are as follows:

- The available bandwidth is severely limited.
- The underwater channel is impaired because of multi-path and fading.
- Propagation delay in underwater is five orders of magnitude higher than in Radio Frequency (RF) terrestrial channels, and variable.
- High bit error rates and temporary losses of connectivity (shadow zones) can be experienced.
- Underwater sensors are characterized by high cost because of extra protective sheaths needed for sensors and also relatively small numbers of suppliers (i.e., not much economy of scale) are available.
- Battery power is limited and usually batteries cannot be recharged as solar energy cannot be exploited.
- Underwater sensors are more prone to failures because of fouling and corrosion [4].

2.8 Mac layer related sensor network properties

Maximizing the network lifetime is a common objective of sensor network research, since sensor nodes are assumed to be disposed when they are out of battery. Under these circumstances, the proposed MAC protocol must be energy efficient by reducing the potential energy wastes.

Types of communication patterns that are observed in sensor network applications should be investigated since these patterns are used to extract the behavior of the sensor network traffic that has to be handled by a given MAC protocol [5].

2.8.1 Reasons of Energy Waste

When a receiver node receives more than one packet at the same time, these packets are called "collided packets" even when they coincide partially. All packets that cause the collision have to be discarded and the re-transmissions of these packets are required which increase the energy

consumption. Although some packets could be recovered by a *capture* effect, a number of requirements have to be achieved for its success. The second reason of energy waste is *overhearing*, meaning that a node receives packets that are destined to other nodes. The third energy waste occurs as a result of *control packet overhead*. Minimal number of control packets should be used to make a data transmission.

One of the major sources of energy waste is *idle-listening*, i.e., listening to an idle channel to receive possible traffic. The last reason for energy waste is *over emitting*, which is caused by the transmission of a message when the destination node is not ready. Given the facts above, a correctly-designed MAC protocol should prevent these energy wastes [5].

2.8.2   Communication Patterns

There are three types of communication patterns in wireless sensor networks:

- Broadcast.
- Converge-cast.
- Local gossip.

Broadcast type of communication pattern is generally used by a base station (sink) to transmit some information to all sensor nodes of the network. Broadcasted information may include queries of sensor query-processing architectures, program updates for sensor nodes, control packets for the whole system. The broadcast type communication pattern should not be confused with broadcast type packet. For the former, all nodes of the network are intended receivers whereas for the latter the intended receivers are the nodes within the communication range of the transmitting node.

In some scenarios, the sensors that detect an intruder communicate with each other locally. This kind of communication pattern is called local gossip, where a sensor sends a message to its neighboring nodes within a range. The sensors that detect the intruder, then, need to send what they perceive to the information center. That communication pattern is called converge-cast, where a group of sensors   communicate to a specific sensor. The destination node could be a cluster head, data fusion center, base station. In protocols that include clustering, cluster heads communicate with their members and thus the intended receivers may not be all neighbors of the cluster head, but just a subset of the neighbors. To serve for such scenarios, we define a fourth type of

communication pattern, multicast, where a sensor sends a message to a specific subset of sensors [6].

2.8.3   Properties of a Well-defined MAC Protocol

To design a good MAC protocol for the wireless sensor networks, the following attributes must be considered:

- Energy Efficiency.
- Scalability.
- Adaptability to changes

The first attribute is the energy efficiency. We have to define energy efficient protocols in order to prolong the network lifetime. Other important attributes are scalability and adaptability to changes. Changes in network size, node density and topology should be handled rapidly and effectively for a successful adaptation. Some of the reasons behind these network property changes are limited node lifetime, addition of new nodes to the network and varying interference which may alter the connectivity and hence the network topology.

A good MAC protocol should gracefully accommodate such network changes. Other typical important attributes such as latency, throughput and bandwidth utilization may be secondary in sensor networks. Contrary to other wireless networks, fairness among sensor nodes is not usually a design goal, since all sensor nodes share a common task.

2.9   MAC layer protocols

A wide range of MAC protocols are defined for underwater sensor networks:
- Sensor-MAC.
- Wise-MAC
- Traffic-Adaptive MAC Protocol.

2.9.1   Sensor-MAC

Locally managed synchronizations and periodic sleep-listen schedules based on these synchronizations form the basic idea behind the S-MAC protocol. Neighboring nodes form virtual clusters to set up a common sleep schedule. If two neighboring nodes reside in two different virtual clusters, they wake up at listen periods of both clusters. A drawback of S-MAC algorithm is this possibility of following two different schedules, which results in more energy consumption via idle listening and overhearing. Schedule exchanges are accomplished by periodical SYNC packet broadcasts to immediate neighbors
.

The period for each node to send a SYNC packet is called the *synchronization period*. Fig. 2.5 represents a sample *sender-receiver* communication.
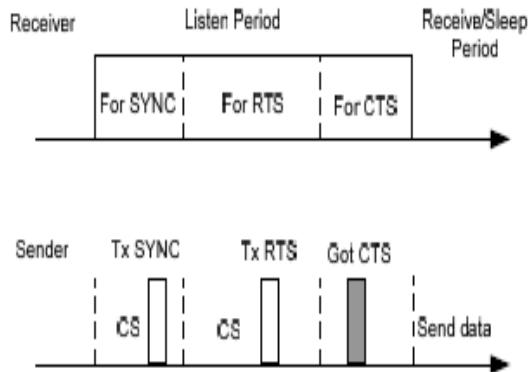

Fig. 2.5: S-MAC messaging scenario

Collision avoidance is achieved by a carrier sense, which is represented as CS in the figure. Furthermore, RTS/CTS packet exchanges are used for unicast type data packets. An important feature of S-MAC is the concept of message-passing where long messages are divided into frames and sent in a burst. With this technique, one may achieve energy savings by minimizing communication overhead at the expense of unfairness in medium access.

Periodic sleep may result in high latency especially for multi-hop routing algorithms, since all immediate nodes have their own sleep schedules. The latency caused by periodic sleeping is called *sleep delay*. Adaptive listening technique is proposed to improve the sleep delay, and thus the overall latency. In that technique, the node who overhears its neighbor's transmissions wakes up for a short time at the end of the transmission. Hence, if the node is the next-hop node, its neighbor could pass data immediately. The end of the transmissions is known by the *duration* field of RTS/CTS packets [5].

2.9.1.1 Advantages

- The energy waste is reduced by sleep schedules.
- Implementation is simple.
- Time synchronization overhead is prevented with sleep schedule announcements.

2.9.1.2 Disadvantages

- Increases collision probability.

- Adaptive listening incurs overhearing or idle listening, if the packet is not destined to the listening node.
- Decreases efficiency.

2.9.2 Wise-MAC

Spatial TDMA and CSMA with Preamble Sampling protocol is proposed, where all sensor nodes are defined to have two communication channels. Data channel is accessed with TDMA method, whereas the control channel is accessed with CSMA method. Wise-MAC protocol uses non-persistent CSMA (np-CSMA) with preamble sampling to decrease idle listening. In the preamble sampling technique, a preamble precedes each data packet for alerting the receiving node. All nodes in a network sample the medium with a common period, but their relative schedule offsets are independent.

If a node finds the medium busy after it wakes up and samples the medium, it continues to listen until it receives a data packet or the medium becomes idle again. The size of the preamble is initially set to be equal to the sampling period. However, the receiver may not be ready at the end of the preamble, due to reasons like interference, which causes the possibility of *over-emitting* type energy waste. Moreover, *over-emitting* is increased with the length of the preamble and the data packet, since no handshake is done with the intended receiver.

To reduce the power consumption incurred by the predetermined fixed-length preamble, Wise-MAC offers a method to dynamically determine the length of the preamble. That method uses the knowledge of the sleep schedules of the transmitter node's direct neighbors. The nodes learn and refresh their neighbor's sleep schedule during every data exchange as part of the acknowledgement message. In that way, every node keeps a table of sleep schedules of its neighbors. Based on neighbors' sleep schedule table, Wise-MAC schedules transmissions so that the destination node's sampling time corresponds to the middle of the sender's preamble.

To decrease the possibility of collisions caused by that specific start time of wake-up preamble, a random wake-up preamble is advised. Another parameter affecting the choice of the wake-up preamble length is the potential clock drift between the source and the destination. A lower bound for the preamble length is calculated as the minimum of the destination's sampling period, Tw, and the potential clock drift with the destination which is a

multiple of the time since the last ACK packet arrival. Considering this lower bound, a preamble length, Tp, is chosen randomly. Fig. 2.6 presents the Wise-MAC concept [5].
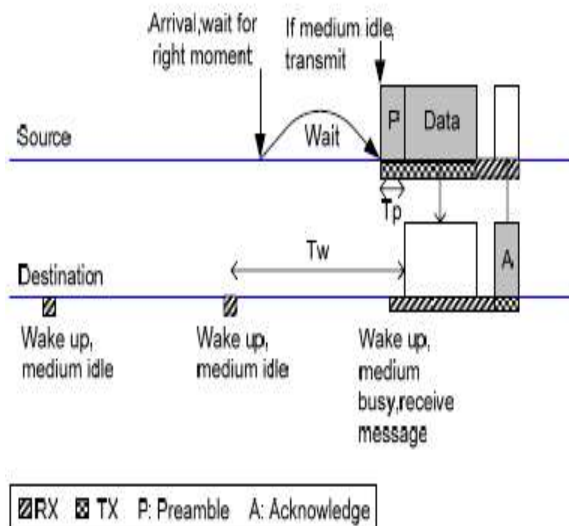

Fig. 2.6: Wise-MAC concept

2.9.2.1 Advantages

 Performance is better under variable traffic conditions.
 Power consumption can be reduced.

2.9.2.2 Disadvantages

 Latency is high.
 Decentralized sleep-listen scheduling results in different sleep and wake-up times for each neighbor of a node.

2.9.3 Traffic-Adaptive MAC Protocol

TRAMA is a TDMA-based algorithm and proposed to increase the utilization of classical TDMA in an energy efficient manner. It is similar to Node Activation Multiple Access (NAMA), where for each time slot a distributed election algorithm is used to select one transmitter within two-hop neighborhood. This kind of election eliminates the hidden terminal problem and hence, ensures all nodes in the one-hop neighborhood of the transmitter will receive data without any collision. However, NAMA is not energy efficient, and incurs overhearing. Time is divided into random-access and scheduled-access (transmission) periods. Random-access period is used to establish two-hop topology information where channel access is contention-based.

A basic assumption is that, by the information passed by the application layer, MAC layer can calculate the transmission duration needed which is denoted as SCHEDULE_INTERVAL. Then at time t, the node calculates the number of slots for which it will have the highest priority among two-hop neighbors within the period [t, t+ SCHEDULE_INTERVAL].

The node announces the slots it will use as well as the intended receivers for these slots with a *schedule packet*. Additionally, the node announces the slots for which it has the highest priority but will not be used. The *schedule packet* indicates the intended receivers using a bitmap whose length is equal to the number of its neighbors. Bits correspond to one-hop neighbors ordered by their identities.

Since the receivers of those messages have the exact list and identities of the one-hop neighbors, they find out the intended receiver. When the vacant slots are announced, potential senders are evaluated for re-use of those slots. The priority of a node on a slot is calculated by a hash function of noa node'snd slthe slot'sdentities. Delays are found to be higher compared to contention-based protocols due to the higher percentage of sleep time [5].

2.9.3.1 Advantages

 Higher percentage of sleep time and less collision probability is achieved compared to CSMA based protocols.
 Since intended receivers are indicated with a bitmap, less communication is performed for multicast and broadcast type of communication patterns compared other protocols.

2.9.3.2 Disadvantages

 Transmission slots are set to be seven times longer than the random access period. However,
 All nodes are defined to be either in receive or transmit states during the random access period for schedule exchanges.

2.10 A cross-layer protocol stack

A protocol stack for uw-sensors should combine power awareness and management, and promote cooperation among the sensor nodes. It should consist of physical layer, data link layer, network layer, transport layer, and application layer functionalities. The protocol stack should also

include a power management plan, a coordinate plane, and a localization plane.

The power management plane is responsible for network functionalities aimed at minimizing the energy consumption (e.g., sleep modes, power control, etc.). The coordination plane is responsible for all functionalities that require coordination among sensors (e.g., coordination of the sleep modes, data aggregation, and 3D topology optimization). The localization plane is responsible for providing absolute or relative localization information to the sensor node, when needed by the protocol stack or by the application [7].

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