CHAPTER 6

CASE STUDY

6.1 Introduction

Water is a crucial resource for all life on earth and it is fast becoming one of the limited natural resources to human kind. It can be foreseen in near future that water, especially drinking water and water for agricultural purposes, becoming a scarce resource. Clean drinking water is already a revenue generating commodity since the past decade. As a consequence it is found that water quality monitoring in a long-term continuous mode is beginning to catch on as an essential component in environmental pollution monitoring and control in many countries [57]. Thanks to the worrying realistic effect from industry waste and climate change. Sensor technologies and wireless communications, both terrestrial and underwater, are being seriously looked into by many researchers to find ways to integrate these technologies for a novel data sensing and collecting network in long-term pollution monitoring systems.

The application of wireless sensor networks in underwater domain has a huge potential for monitoring the health of river, lake, reservoir, and marine environment. By deploying the in-situ sensors for continuous sampling of the environmental parameters or indicators offers the advantage of reducing operation costs and to provide real-time information on pollutant fluctuations. Essentially, the UWSN monitoring system comprises of a network of underwater sensors deployed at key locations for a time frame of months in a continuous operation mode. The sensed data from the sensors will be communicated by wireless means via an acoustic channel to a data collection center for processing and interpretation. It is believed that judicious deployment of underwater sensor network is a promising solution for long-term water quality surveillance.

A handful of UWSN have been deployed for water quality/pollution monitoring and two prominent works in this area are briefly mentioned here. SmartCoast [58] was a project aimed to develop a wireless sensor network with a distinct "plug-and-play" feature that incorporates novel sensor nodes and low power consumption. This system was based on Zigbee communications standard. The "plug-and-play" platform was designed to sense pH level, temperature, conductivity, depth and turbidity.

In [59] the Fraser River Water Quality System, which was a project initiated for monitoring water quality and meteorological parameters in real-time mode all year round. A moored buoy platform was used for station location and in-situ water sampling. A three meter tall Oceanographic-Data-Acquisition-System (ODAS) buoy was designed for this purpose. The monitoring was scheduled in continuous mode with a biweekly sampling. ODAS was claimed to be able to distinguish tidally driven events to initiate sampling of organic contaminates.

Practically there are three general network scenarios for UWSN deployment: static two-dimensional UWSN for underwater bottom environment monitoring, static three-dimensional UWSN for underwater column monitoring, and three-dimensional mobile network with autonomous underwater vehicles [6]. However, in terms of aquatic applications, UWSN can be classified into two categories: long-term non-time critical aquatic monitoring, and short-term time critical exploration [60]. The case study to be described in this chapter falls in the first category. The case study is about a long-term water pollution monitoring application. Other applications fall into the first category may include marine biology, oceanography, ocean floor seismic monitoring, etc. As for the second category, the applications may include setting up of ad-hoc UWSN at the site of a shipwreck for liquid toxic leakage monitoring, radiation detection, etc.

This chapter is organized as follow: Section 6.2 describes the possible UWSN architecture for underwater pollution monitoring applications. This include a description of a basic architecture in section 6.2.1 and an extended architecture in section 6.2.2. This case study focuses on the extended architecture. The details of data transmission and data acquisition scheduling process for the proposed UWSN is described Section 6.3 and this leads to a scheduling algorithm being proposed in section 6.4. Section 6.5 highlights the sink node battery power capacity issue and proposed a battery power capacity estimation method. Section 6.6 concludes this chapter.

6.2 Underwater Sensor Network Architecture

6.2.1 Basic Underwater Sensor Network Architecture

UWSN are basically a network based on sensor nodes equipped with sensors and acoustic modems for communications [61]. Figure 6.1 shows a basic 2D static architecture that may be used for underwater environment monitoring.

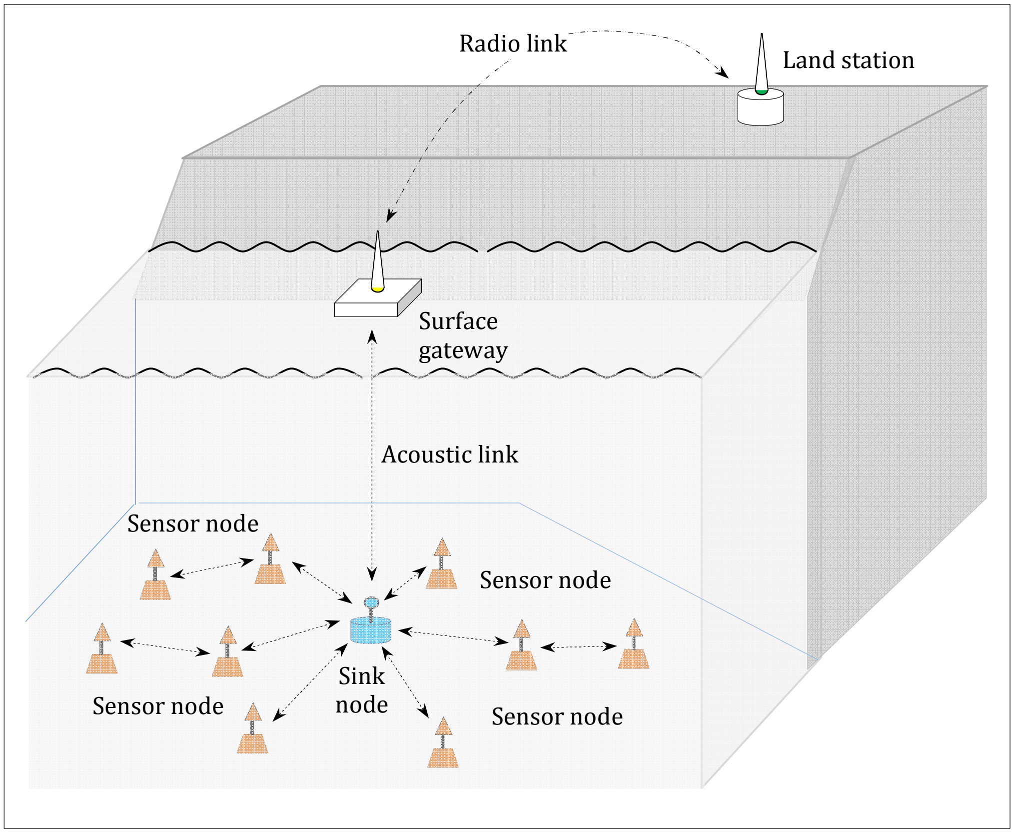

Figure 6.1: Basic UWSN architecture for underwater environment monitoring

All sensor nodes and the sink node(s) are stationed at their respective fix/static locations at the water bottom for data collection purposes. These nodes can be connected in a star-, a tree-, or a hybrid of star-tree-topology. All the nodes are allowed to communicate with each other in sending their own data, and also to forward data from other nodes, to a sink node in a multi-hop manner. It follows that the sink node that communicates directly with the surface gateway would need a high capacity power supply in the fact that it has to relay data packets from all the other nodes to the surface gateway.

Two acoustic modems are available on the sink node. One is used to communicate with the sensor nodes in the network and the other one is to communicate with a moored gateway placed on the water surface. The gateway is equipped with a radio link to relay data packets to a land station. The land station shall provide monitoring and control of the data acquisition of all sensor nodes in ad-hoc real-time mode or in long-term time scheduled mode [62].

6.2.2 Underwater Sensor Network Architecture for Water Column Monitoring

With reference to the basic UWSN architecture in Figure 6.1 and the relevant works presented in the previous chapters, the architecture for the case study is shown in Figure 6.2. This architecture is aimed for shallow water deployment such as at coastal areas, lakes, reservoirs, etc for a long-term non-time critical water pollution or water quality monitoring. The overall architecture represents a static 3D network topology and it is seen as the extension to the basic static 2D topology shown in Figure 6.1.

Static 3D architecture in fact is foreseen as one of the most suitable setups for long-term environmental monitoring application [63]. The sensor nodes and the sink nodes are practically arranged, by some means of anchoring mechanism, into tiers forming a column of sensing network in a body of water. All nodes are considered to be non-mobile or having limited mobility of about 3 to 5 knots or 1 to 1.5 m/s due to typical underwater current [63].

The number of tiers in the topology depends on the depth of the water body to be monitored and the pollution monitoring resolution requirements. Naturally higher resolution demands more tiers and more sensor nodes per tier. Take note that Figure 6.2 shows an architecture with each tier represents a disk-like star topology with a centralized sink node.

Typically the top tier is placed about 30 to 50 meters away from the water surface to avoid acoustic wave reflection complications near the water surface. This precaution is also applicable to the tier of sensor/sink nodes one layer above the ground tier to avoid wave reflection due to ground surface.

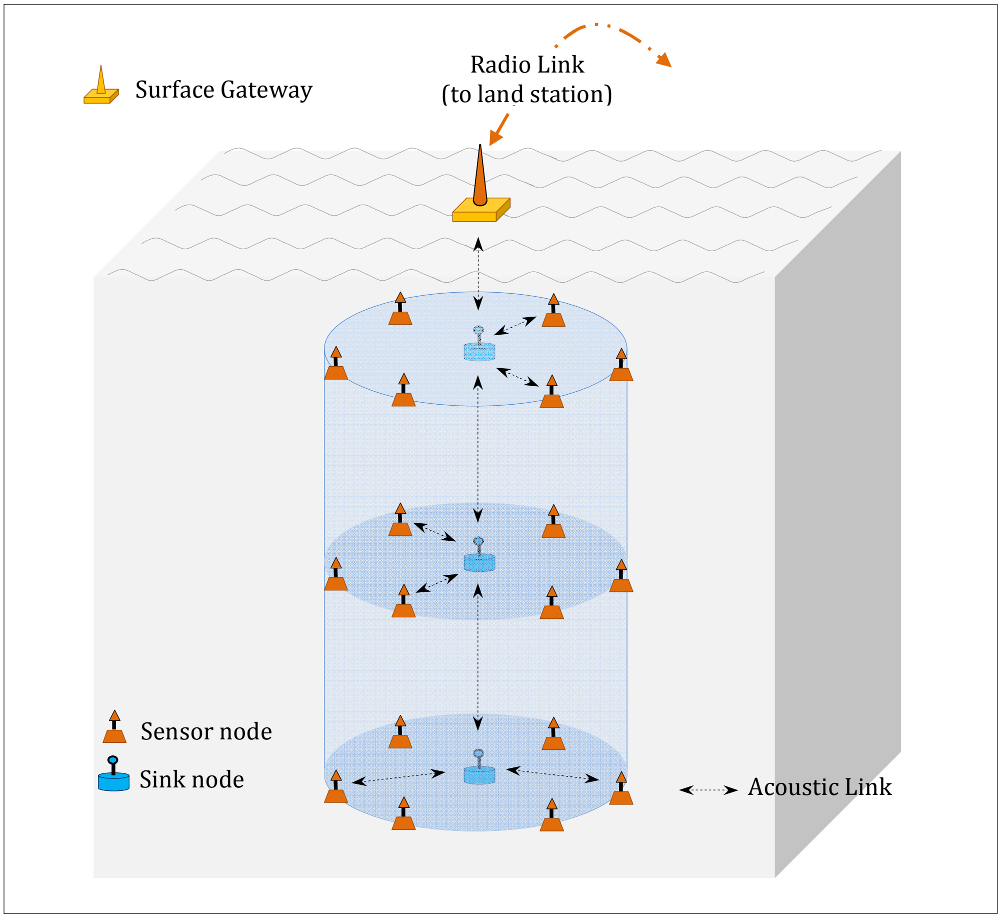

Figure 6.2: UWSN architecture for underwater pollution monitoring

At each tier, the distance between the sink node and all the sensor nodes is arranged in such a way that it is for a one hop data transmission. This is to be consistent to the works presented in the earlier chapters. In practice, the actual distance/range shall depends on the transmission range of the sensor nodes and the acoustic modem deployed.

The sink nodes are also placed at a distance for one hop transmission. Again this range is to be in line with the research works in the preceding chapters. The total number of sensor nodes to be deployed at each tier is very much dependent on the network deployment budget considering that underwater sensor/sink nodes are, very often, costly items.

As illustrated in Figure 6.2, each tier consists of a centralized star topology whereby a sink node at the center is surrounded by several sensor nodes. All the nodes at each tier can be quantified as a set of nodes represented by $N = \{n_1, n_2, ... n_s\}$ with n_s acting as a static sink node. If the transmission range of each sensor node is l and each node is of omnidirectional type then a one hop link can exist between a sensor node and the sink node if and only if $|L_{is}| \leq l$, where L_{is} is the distance between a sensor node n_i and the sink node n_s. Therefore the overall network can be viewed as a 3D column having an approximated volume of $2\pi(L_{is})^2H$, where H is the height measured from the sink node at the bottom tier to the surface gateway.

For this case study, it is assumed a 3-tier network. In each tier the distance between the sensor nodes and the sink node is to be 50m. The sink node to sink node distance is also set to 50m and the surface gateway is 50m away from the top tier sink node. In such arrangement, each tier is able to cover approximately 8000m^2 of a disk-like area and for a 3-tier setup the column height would be 150m. Therefore this setup is able to monitor a water-column having a volume of approximately 1.2 million m^3. Note that all the distances in this case study are chosen to be practically applicable in a shallow water environment.

It should be mentioned here that for a more inclusive and practical network setup the cluster of sensor nodes in a tier do not have to be anchored at the same height as the sink node. This is to avoid forming a disk-like shape topology that has a more restricted water-body volume and in return offers a lower monitoring resolution. The sensor nodes at each tier can in fact be anchored at different height to cover a larger monitored volume and yet keeping intact the one hop transmission range within the sink node coverage. Take note that the single column network architecture in Figure 6.2 can be duplicated several times over should the area to be monitored is broad and wide.

Take note also that the types of sensor node to be deployed in the proposed monitoring network and the types of pollutant to be monitored by the sensors are not the scope of this case study. They belong to the field of sensor technology and pollutant sensing or measurement. This case study is emphasizing more on the underwater one hop data transmission scheduling for the sensed data (in relation to the proposed network architecture/topology) and also on the integration of the proposed 2Q algorithm into the data transmission scheduling process. Therefore, in this case study, it is assumed that all sensor types are appropriately chosen per their sensing specifications for sensing the relevant pollutants and are able to generate data packets having the generic format shown in Figure 3.2 on page 43.

An addressing scheme using the address byte format shown in Figure 6.3 is hereby suggested to uniquely identify the nodes in the proposed network. The address byte shall comprise of three fields: T, S, and N field. These fields literally stands for Tier , Sink , and Node.

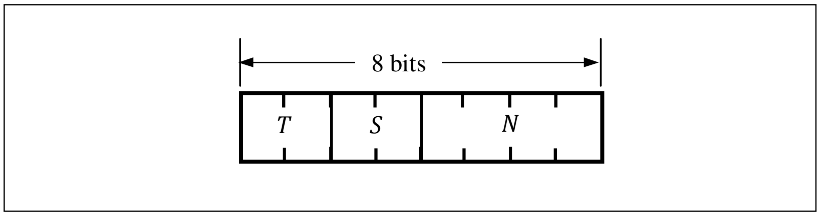

Figure 6.3: Address byte format

The two bits in the T field are for the network tiers identification or addressing. The two bits in the S field are for the sink nodes identification/addressing, and the four bits in N field are for the sensor nodes identification/addressing. Be aware that the address byte shown in Figure 6.3 can be used to address or access: a maximum of 4 tiers, a maximum of 4 sink nodes, and a maximum of 16 sensor nodes. Based on digital system numbering sequence convention, the numbering of tiers, sink nodes, and sensor nodes starts from ‘0’. For instance in Figure 6.2, Tier 0 is the ground tier and Tier 2 refers to the tier nearest to the surface gateway. Note that the suggested addressing scheme can be easily expanded into a generic form to accommodate more address bytes for accessing larger number of nodes/sinks in a large network.

Symbolically the nodes in Figure 6.2 can be accessed with an address byte having the form of $<T_i:S_j:N_k>$, where i,j,k are integers starting from ‘0’. T_i represents the tier to be accessed, S_j the sink node to be accessed, and N_k the sensor node to be accessed. Taking the network in Figure 6.2 for an example, $<T_1:S_1:N_6>$ is a valid address that belongs to sensor node 6 which has a one hop link with sink node 1 at tier 1. Thus the address byte would have these bits: 01010110. For address byte: 01100110 which translate to $<T_1:S_2:N_6>$ would be considered an invalid address because there is only one sink node at tier 1 in Figure 6.2. However this address is valid if there exists an additional similar column in the network.

6.3 Data Transmission and Data Acquisition

As stated above, the proposed UWSN is aimed for a long-term non-time-critical water pollution monitoring. It means this UWSN is not to be an ad-hoc network and its deployment duration can be defined for a minimum of 3 months to a maximum of one year. Typically it is between 3 to 6 months depending on the water quality when the nodes need to be taken out for occlusion maintenances.

For non-time-critical monitoring applications, data acquisition is normally time scheduled rather than event triggered. This implies that data transmission would be in time scheduled mode as well. Data transmission can be invoked immediately when a sensor has acquired a data or alternatively, to conserve energy, the data acquired may be aggregated into a group and send as a data group to the sink at some specific scheduled time slot. An efficient dynamic frame aggregation scheme proposed by [64] may be adopted for this approach.

For this case study the author shall adopt one of the more commonly used approach is for time scheduled data transmission and acquisition – the Time Division Multiple Access (TDMA) method. It should be mentioned here that Frequency Division Multiple Access (FDMA) is not applicable in underwater acoustic channel due to its severe bandwidth limitation.

Fundamentally TDMA is a mechanism that allows a cyclic assignment of a time slot for each of the network node to transmit data or to acquire data. In TDMA scheduling some form of time synchronization procedures may be necessary to minimize the 'timing drift' problem due to the nodes' hardware based timing requirements. A generic timing diagram of TDMA scheduling adopted from [66] is shown in Figure 6.4.

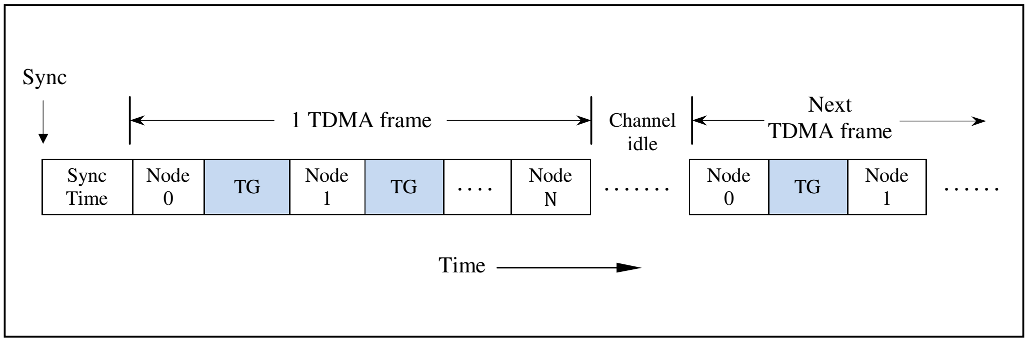

Figure 6.4: Generic timing diagram of TDMA scheduling

This timing diagram shows the time slot allocated for each node to transmit its data packets to the sink node in sequential manner. At each allocated time slot the acoustic channel/link is reserved for one particular sensor/sink node only. This is one of the TDMA properties in eliminating channel contention among the sensor/sink nodes for preventing data collision. Due to the relatively slow speed of acoustic wave (nominally accepted as 1500m/s), which is in the order of 5 times slower than RF wave, time guard (TG) intervals need to be inserted in between the node transmission time slots to prevent transmissions overlapping and interfering with transmissions in other time slots.

In this case study the basic implementation concept of TDMA time-scheduling scheme for data transmission shall first be explained with reference to a single tier network topology. After which the basic concept is extended to the multi-tier topology of Figure 6.2. A prerequisite for the implementation of this scheme is that all sensor nodes in a particular tier must have completed their data acquisition cycle i.e. already holding the sensed data in their respective data queue before the sequence of data transmission for that particular tier is kicked-off.

The whole TDMA scheduling sequence starts off with a Sync signal being broadcast from the sink node at a particular tier to all sensor nodes in that particular tier. The sink node initiates the broadcasting of Sync signal upon receiving a data collection command from the time scheduler located at the land station via the surface gateway. Alternatively data collection command can be initiated by the surface gateway itself. Since all sensor nodes are just one hop away from the sink therefore this Sync signal is able to synchronize simultaneously the timing requirement in each sensor node.

Upon receiving the Sync signal each sensor node will take a duration of Sync Time to complete their respective time synchronization process. It is worth mentioned here that the actual Sync Time duration is device dependent. Therefore it is best to have homogeneous modem for all nodes in the entire network. After synchronization, Node 0 is given a specific time slot to exclusively use the acoustic channel to transmit its data to the sink. A Time Guard interval is inserted at the end of Node 0 transmission. After which Node 1 will have the exclusive right to use the channel to transfer its data to the same sink. This procedure is repeated until the last sensor node in the tier, Node N, completed its data transfer. At this juncture 1 TDMA time frame is considered to be consumed and one scheduling sequence (or cycle) is over. The channel shall then goes into idle state until the next sequence/cycle is initiated. At the idle state all nodes shall go into sleep mode to preserve energy or shall wake up periodically to perform data acquisition tasks. For information, the computation of a time slot duration and the TG duration is explained in the next section.

For long-term non-time-critical underwater pollution monitoring application, it is common to have the sensor nodes configured with data acquisition rate in the range of tens of minutes per acquisition. It is also common to have an acquired data being sent to the assigned sink node as soon as it is made available in the sensor node. This simply means the data transmission rate is normally in sync with the data acquisition rate. So the consequence of configuring the data transmission/acquisition rate to tens of minutes per data sampling is that the channel idle time will be very much longer than the TDMA time frame. Hence a portion of this channel idle time can be utilized by the sink node to transfer the data that it has collected, from all the sensor nodes under its custody, to the surface gateway.

The sink node in such a situation is, of course, expected to have storage capacity large enough to aggregate the data packets from all nodes in 1TDMA time frame. Take notice that multi-hop transmission is necessary for the bottom sink to transmit its data packets via some intermediate sinks to the surface gateway unless the UWSN is of a 2D static architecture where the sink node is directly linked to surface gateway.

The basic one-tier TDMA scheduling scheme explained above can be extended to suit the multi-tier UWSN architecture. In its simplicity, the multi-tier architecture simply needs a multi-frame TDMA scheduling. That is, it is the cyclic assignment of TDMA time frame (refer to Figure 6.4) to each of the tier in the multi-tier network. The timing diagram in Figure 6.5 can be used to illustrate this concept. This timing diagram shows the scheduling in a network with M tiers and therefore there are M TDMA frames.

An inter-frame time guard (IFTG) is needed in between two TDMA frames and inside each TDMA frame there are intra-frame time guards (TG). For multi-tier network all sink nodes, except the top most sink, need to do multi-hop transmission to relay data packets up to the surface gateway. Therefore it is necessary to have IFTG as a reserved time slot for multi-hop data delivery. For static 3D deployment, a network with M tiers would need an IFTG of Mt_{hop} units time where t_{hop} is the time for one-hop transmission based on the specification that the sink nodes are placed one-hop away from each other. T_{SS} in each TDMA frame is the time slot reserved for the sink node to transfer the aggregated data packets to the sink node one tier or one-hop away.

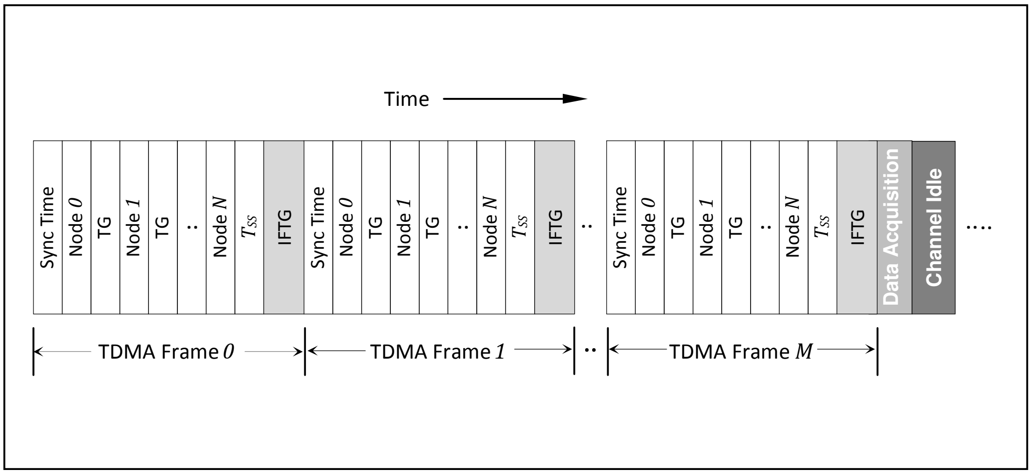

Figure 6.5: TDMA scheduling for multi-tier single column UWSN

With reference to Figure 6.5 it can be seen that the whole cycle of multi-frame TDMA scheduling starts off from TDMA Frame *0*. This time frame allows all sensor nodes at tier 0 to be appropriately scheduled to transmit their data packets to the sink node at tier 0. After collecting the data packets from each of the sensor node this sink node is then allocated a time slot of T_{SS} to transfer these packets to the adjacent sink node i.e. the sink node just one tier above it (one-hop away).

Next an IFTG time slot is allocated to this sink node to ensure the aggregated packets can reach the surface gateway via a multi-hop relaying process. The objective of having multi-hop data transmission for the sink-to-sink route is to better conserves energy in the sink nodes. Multi-hop transmission is known to be more energy efficient than long range direct transmission approach. It is not difficult to see this advantage especially in considering the power needed by the bottom sink to transfer data packets directly to surface gateway instead of using the multi-hop route. At the end of IFTG time slot the scheduling of all nodes in tier 0 is considered complete at this point of time. The whole sequence is now repeated for TDMA Frame *1* to take care for the scheduling of the sensor nodes and the sink node placed at tier *1*. The scheduling process goes on in this manner until the M^{th} tier is being served.

At the end of the last (M^{th}) IFTG time slot the surface gateway shall send a data acquisition signal to all the sink nodes, again, via multi-hop transmission. Upon receiving the signal from the surface gateway, all sink nodes will broadcast this data acquisition signal to all the sensor nodes within its range to initiate sensor's data acquisition processes respectively. A form of time scheduling is needed here for the sinks to broadcast the data acquisition signal to their respective sensor nodes to prevent signal collision. Finally the channel goes into idle state waiting for the next cycle of scheduling to be initiated by the command from the scheduler at the land station.

It should be highlighted here that there is an inherent issue in time synchronization to ensure smooth scheduling of data acquisition and data transmission. At certain occasions some form of synchronization protocols may be needed to keep most of the nodes in sleep mode so that the active nodes at any time are sparsely distributed to reduce the probability of channel contention and data collisions. However in this case study this issue does not pose a serious problem because there is only one active node at a time busy transferring data packets.

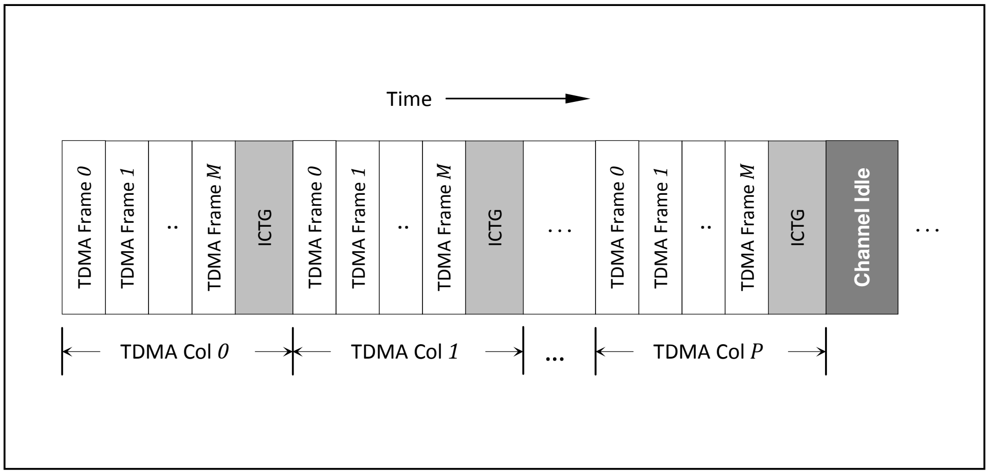

Figure 6.6: TDMA scheduling for UWSN with multiple tiers and columns

The whole cycle of multi-frame TDMA scheduling described above applicable to the one column multi-tier architecture depicted in Figure 6.2. By extending this concept another step further, this one column multi-tier scheduling scheme can be applied to a multi-column multi-tier UWSN architecture. The fundamental timing diagram for such implementation is presented in Figure 6.6 above. However the details and/or the variant of this timing diagram and its related TDMA scheduling sequence are left as a further research direction for the interested readers. The ICTG label in Figure 6.6 is the acronym for Inter-Column Time Guard. This timing diagram assumes there are *P* columns in an arbitrary UWSN.

6.4 Scheduling Algorithm and Time Slot Calculation

6.4.1 Scheduling Algorithm

The multi-frame TDMA scheduling algorithm for the proposed single column multi-tier UWSN architecture shown in Figure 6.2 is presented here. The algorithm is to based on the timing diagram shown in Figure 6.5. Some of the essential prerequisites for the algorithm are listed below. These prerequisites are needed to fulfill the requirements of the components (time slot) in the TDMA time frames. For information, this algorithm is by no means exhaustive. Its variants can be derived from the desired network architecture.

Prerequisites:

- All nodes are of homogeneous type so that all sensor modems have same hardware configurations and specifications to support constant Sync Time. That is, the Sync Time is derived from these homogeneous specifications.
- The sensor nodes have completed their respective data acquisition process and are holding the latest acquired/sensed data in their data queue.
- The time slot for each sensor node to send its data packet to the sink node has been properly computed (see sample calculation in next subsection).

- Duration for TG, T_{SS}, IFTG time slots have been computed accordingly fulfilling their respective requirements (refer to the sample calculations in the next subsection).
- Each TDMA frame is referenced with the general format of $TDMA\_frame\_i$ where $i = 0,1,2 \ldots M$ with $TDMA\_frame\_0$ belongs to the scheduling time frame for the cluster in the lowest tier (furthest away from the surface gateway), and $TDMA\_frame\_M$ for cluster in the highest tier (nearest to the surface gateway).
- There are M tiers in the water body column to be monitored.
- There are N sensors in each tier.
- By default one cycle of scheduling sequence starts from $TDMA\_frame\_0$.
- The BER (p) of the link has been predetermined.
- The distance (l) between sensor-sink and sink-sink pair has been predetermined.
- Data transfer rate (R) has been predetermined.

Algorithm:

```
1:  Surface gateway : receive($Sync$) signal from land station scheduler;
2:  Surface gateway : send($Sync$) via multi-sink route to $sink_0$ at lowest tier;
3:  for ($i = 0$ ; $i <= M$ ; $i$++) /*for TDMA frame scheduling control*/
4:     {$TDMA\_frame\_i$ :
5:         $sink_i$ : broadcast($Sync$) to $sensor_0$ .. $sensor_N$ ; /*for $tier_i$*/
6:         $sensor_0$ .. $sensor_N$ : synchronize($timer$);
7:         for ($j = 0$ ; $j <= N$ ; $j$++) /*for $tier_i$ sensors scheduling control */
8:             {$node_j$ : invoke 2Q algorithm for optimal($packet\_size$);
9:               $node_j$ : send($data\_packet$) to $sink_i$;
10:              allocate $TG$ time slot for ($data\_packet$) to reach $sink_i$;
11:              $sink_i$: store($data\_packet$);
11:            }/*repeat from step 8*/
12:        $sink_i$: invoke 2Q algorithm for optimal($aggregated\_data$);
13:        allocate $T_{SS}$ time for $sink_i$ : send($aggregated\_data$) to $sink_{i+1}$;
14:        allocate $IFTG$ time slot for ($aggregated\_data$) to reach surface gateway;
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15:     surface gateway: send(aggregated_data) to land station;
15:   }/*repeat from step 4*/
16:   surface gateway: send(data_acquisition) signal to all sinks via multi-hop
      transmission;
17:   all sinks: broadcast(data_acquisition) signal to all sensor nodes to
      initiate data acquisition process based on predefined broadcasting
      scheduling;
18:   channel idle: all nodes go into sleep mode.
19:   TDMA scheduling cycle repeat from step 1 on next command initiated
      from land station scheduler to the surface gateway.
```

6.4.2 Sample Time Slot Calculation

Samples of time slot calculation are hereby given in response to the timing diagram shown in Figure 6.5 and the prerequisites listed in the preceding subsection.

Time slot for a sensor node and its TG duration:

Parameters needed:

B_n : Total data bits (payload) sent by a node.
l : Distance between the source-sink pair in meter.
c : Nominal speed of sound in underwater (1500 m/s).
B_h : Header (sensor node address + sink node address) bits.
R : transmission bit rate in bps.

Total bits send out by a node = $B_n + B_h$
$\therefore$ Time needed for a node = $(B_p + B_h)/R$ s
$TG = 2l/c$ (Note: $2l$ is for worst case latency)

Example: A sensor transmits 3 bytes of sensed data at a rate of 1000 bps to a sink 50m away using the address format shown in Figure 6.3.

Time needed by a node $= (3\times 8 + 8 + 8)/1000 = 40$ ms.

$TG = 100/1500 = 66.67$ ms.

Time slot for a sink node (T_{SS}):

Parameters needed:

NB_n : Total data bits (payload) aggregated from N sensors nodes.

l : Distance between the sink-sink pair in meter.

c : Nominal speed of sound in underwater (1500 m/s).

B_h : Header ($sink_i$ address + $sink_{i+1}$ address) bits.

R : Transmission bit rate in bps.

Example: A sink transfers data bytes aggregated from 8 sensor nodes (with each sensor producing 3 bytes of sensed data) at a rate of 1000 bps to a sink 50m away using the address format shown in Figure 6.3.

Time needed by a sink node $= (8\times 3\times 8 + 8 + 8)/1000 = 208$ ms.

$TG = 100/1500 = 66.67$ ms.

$\therefore\ T_{SS} = 208 + 66.67 = 274.67$ ms (Note: T_{SS} is a one-hop time)

Time slot for IFTG :

Parameters needed:

T_{SS} : Time for one hop.

M : Number of tiers in the network.

$IFTG = MT_{SS}$ in seconds = 824 ms for 3 tiers network.

Note: All calculations are based on the worst case scenario. Other variants do exist and it is left as a topic for possible further research to the interested readers.

6.5 Battery Power Capacity Estimation

The finite battery power source in the sensor/sink nodes is always an important issue in UWSN (in fact in WSN too). Battery energy conservation hence becomes an important factor in enhancing the life span of the entire network. The sensible strategy is to have the nodes stay in idle/inactive mode more often than in the active mode to conserve energy. The power consumption in some of the commercial acoustic modems shown in Table 6.1 [65] aptly manifest the reason for this preference. One of the solutions is to enhance network lifespan is to have the power capacity of the battery be sufficiently large enough to support a long-term network deployment to avoid frequent battery recharging or replacement.

Table 6.1 Acoustic modem power consumption

State	LinkQuest	EvoLogics	WHOI
Transmit	1 – 12W	2.5 – 40 W	50 – 100W
Receive	0.8W	5 – 50 mW	0.1 – 2 W
Idle	8 mW	3 mW	0.1 – 0.25W

This section presents a network battery power capacity estimation method specifically for long-term non-time-critical UWSN applications based on the architecture illustrated in Figure 6.2 and the scheduling algorithm explained in subsection 6.4.1. It is hope that the estimation method described would be general enough for adoption in other types of UWSN architecture.

In general, the topology in Figure 6.2 shows that each tier has a cluster of sensor nodes monitoring their surrounding conditions to periodically send the acquired (and processed) data to a central sink at the same tier. Subsequently the sink shall aggregates the processed data packets and send them to a central surface gateway. The main source of power consumption at each node is when the node is transmitting data packets and when it is receiving data packets.

Technically, the node’s sensing and processing power consumptions are assumed to be negligible [67],[68]. This statement holds true for this case study because the data acquisition frequency/rate in the proposed UWSN is in the order of tens of minutes per sampling [69],[70]. Therefore power consumption in data sensing and processing in the nodes is not considered a major issue.

A closer look at Figure 6.2 reveals that the water-body column represents an architecture of 3 tiers with 3 chained clusters. In the context of data transmission, the sensor nodes at each tier formed a cluster in star topology (with a centralized sink node) where the sink nodes formed a chained topology. Collectively the nodes in the water column represents a linear chained network. This implies that the sink node at the uppermost tier is the candidate of bottleneck in terms of its battery lifetime and thus is the main factor affecting the whole network lifespan.

It is not difficult to see the reason for this by recalling the TDMA scheduling scheme explained in section 6.4. The uppermost sink node practically carries the burden of transmitting the data packets of all other nodes in the whole network to the surface gateway. This node would certainly deplete its energy quickest, and worst, if it is downed or failed the whole network is downed with it. Putting the probability of the node’s technical failure aside, estimating the battery capacity of this particular node is of special interest for estimating the UWSN lifespan. In a nutshell, if the battery capacity of the uppermost sink can be determined then the lifespan of the whole network can be quite easily estimated. It follows that the battery capacity (or lifetime) of all other nodes can be readily derived from the lifetime of the uppermost sink node.

It should be mentioned here that the battery capacity and the lifetime of the surface gateway is not an issue. This is because this gateway can be conveniently powered by a solar source and/or complement with a rechargeable battery. Moreover changing or replacing the power supply unit in this node is not a difficult task at all. It is therefore safe to assume technically that the surface gateway has infinite power supply. It follows that the estimation method presented in this section will not include this gateway.

Three important parameters have been identified from the topology in Figure 6.2 for estimating the battery power capacity of a node. They include:

1. The sensor node data acquisition frequency. It is understood that higher data acquisition frequency/rate causes the nodes to stay active more frequent thus consuming more power. This parameter is denoted as D_f. The data acquisition frequency in this case study is made with reference to the works in [69],[70].
2. The signal transmission range between nodes. Transmission process consumed the most power in a node (cf Table 6.1) and unfortunately higher power is needed for long range data transmission. This parameter is denoted as S_R. However for this case study the distances between nodes are kept at a constant of 50m.
3. The number of sensor nodes in a cluster. More sensor nodes aptly means more energy would be drained off from the cluster sink since more data packets need to be transferred to/through it. This parameter is denoted as N. Note that N is related to D_f. It is not difficult to see how power consumption in the sink node can quickly becomes an issue when N is large and D_f is high. As far as power consumption is concerned the choice of N is considered an important network design factor.

The battery capacity of a node in the network shown in Figure 6.2 can be derived from the basic transmitter power equation given in [71]. It is restated here as:

$$P_T = 2\pi \times 1\text{m} \times D_w \times I_T$$

where,

P_T is the transmitter power to achieve an intensity of I_T at a distance of 1m in the direction of the receiver node measured in Watts.

D_w is water depth measured in meter.

I_T is power intensity at a distance of 1m from the source in unit of W/m^2.

However the power intensity at 1m from the source can be written as:

$$I_T = 10^{SL/10} \times 0.67 \times 10^{-18}$$

where,

SL is the source signal level in $dB\ re\ \mu Pa$ and I_T is converted into W/m^2 with the conversion factor of 1 μPa = 0.67×10^{-18} [72],[73].

The source signal level (SL) can be derived from the basic passive sonar equation found in [71],[73] as:

$$SL = SNR + TL + (NL - DI)$$

where,

SNR is signal-to-noise ratio (figure of merit) at the receiver node.
TL is transmission loss.
NL is underwater ambient noise level.
DI is source signal directivity index.
Note: All the parameters are quantified in $dB\ re\ \mu Pa$.

By taking the following considerations for shallow water environment:

(i) With the nodes transmitting signal in omnidirection, $DI = 0$.
(ii) Recommended nominal value of NL = 70 $dB\ re\ \mu Pa$ [71],[74].
(iii) Recommended nominal value of SNR = 30 $dB\ re\ \mu Pa$ [71],[75].

The SL expression can now be simplified into:

$$SL = TL + 100\ \ dB\ re\ \mu Pa$$

In shallow water acoustic communications the acoustic signal is considered to propagate in “cylindrical spreading” mode and the transmission loss (TL) in $dB\ re\ \mu Pa$ for cylindrical propagation mode has been derived in [71],[75] as:

$$TL = 10\log S_R + \alpha S_R \times 10^{-3}$$

where,

S_R is the range between a source node and a sink node in meter.
α is the frequency dependent medium absorption coefficient in dB/km.

The frequency dependent absorption medium coefficient (α) can be evaluated with reference to the works of [76],[77] as below where α is in dB/km and f in kHz:

$$\alpha = \begin{cases} 6.01 \times f^{\,0.8552} \times 10^{-2} & 1 \le \mathrm{f} \le 6 \\ 9.7888 \times f^{\,1.7885} \times 10^{-3} & 7 \le \mathrm{f} \le 20 \end{cases}$$

Note: (i) α is valid for temperatures between 4°C and 20°C.
(ii) Variants of α can be found in [78],[79].

Now let's look at an example: For a source-to-sink distance (S_R) of 50m with transmission frequency (f) of 8 kHz (as a typical voice range frequency adopted in underwater acoustic transmission) the following parameters can be obtained:

α = 0.404 dB/km
TL = 17 $dB\ re\ \mu Pa$
SL = 117 $dB\ re\ \mu Pa$
I_T = 0.336×10^{-6} W/m^2

Therefore for a node placed at a depth of 50m, the power needed to transmit a signal such that a SNR of 30 $dB\ re\ \mu Pa$ is to be desired at the sink, can be calculated as:

$$P_T = 2\pi \times 50 \times 50 \times 0.336 \times 10^{-6} = 5.3\text{mW}$$

Then let the number of sensor nodes in a cluster (in a particular tier) be N and each sensor node in this cluster will send B bytes of data acquired per data sampling process to the sink node (at the same tier). So the sink node would have to receive NB bytes (or $8NB$ bits) of data and then transmit all these bits to the next sink node which is S_R meters away. This whole event is considered a "receive-and-transmit" session for a sink node.

For a conservative analysis, $8NB$ bits can be translated approximately into $8NB$ signals in a sink node transmission. This means the power requirement at the sink node per data transmission can be derived as $8NBP_T$ watts. However, do bear in mind that the sink node will also consume power when receiving data bits. Typically the receive-power consumption is around one-fifth of the transmit-power in various commercially available acoustic modems [65],[77]. Thus the total power consumption per data reception and transmission at the sink node can be written as:

$$P_S = 8NBP_T + 8/5(NBP_T) = 9.6NBP_T \text{ watts.}$$

If the sensor node data acquisition frequency (or rate) is D_f, where D_f is quantified in samples/day, then the power consumption of a sink node in a day would be:

$$P_D = D_f P_S \text{ watts.}$$

At this juncture the power consumption per day in a sink node in a particular tier has been derived.

As mentioned earlier, the lifespan of the network shown in Figure 6.2 is practically depending on the battery power capacity of the uppermost sink node. Thus it is important to know the power requirement of this node. Notice that the uppermost sink node is the last node in a chain of sink nodes in terms of data transmission. Essentially this sink node is responsible to relay data packets to the surface gateway forwarded by the sink nodes in other tiers plus data packets from its own cluster nodes. Hence for an M tiers network the power requirement for the uppermost sink node can be computed as:

$P_U = MP_D$ Watts/day ; P_U means the power for uppermost sink

With the value of P_U known, the battery power capacity needed by this node to support the network for a duration of say, D_y days, can be readily obtained by multiplying D_y with P_U. It should be pointed out at this point that the power capacity estimation presented above did not take into consideration the packet header bits. The header bits may vary from one application to the others so is not included in this estimation analysis. Power capacity estimation with header bits could be a further research direction for the interested readers. Now an example is hereby given below to illustrate the power capacity estimation calculation.

Let's make some assumptions based on the network in Figure 6.2:

- There are 8 sensor nodes in a cluster ($N = 8$).
- Each sensor node needs 3 bytes to hold a sample of acquired data ($B = 3$). Note: A 24-bit resolution is acceptable for a data sample in most cases.
- Sensor node is scheduled to perform 1 data sampling every 30 minutes throughout a day (24 hours).
- The power requirement for a sink to transmit a signal is taken from the example above i.e. $P_T = 5.3$mW. Note: S_R is 50m.
- It is a three tiers network ($M = 3$).
- It is one hop transmission for data packets.

The calculation:

The power requirement per data "reception-and-transmission" session for the uppermost sink node is,

$$P_S = 9.6 \times 8 \times 3 \times 5.3 \times 10^{-3} = 1.2 \text{ W}.$$

For 1 data sampling per 30 minutes, therefore the sampling frequency per day would be,

D_f = 48 samples per day.

The total power consumption for a sink node per day is then,

$$P_D = 48 \times 1.2 = 57.6 \text{ W}.$$

Hence the power requirement for the uppermost sink node per day with respect to a 3-tier arrangement would be,

$$P_U = 3 \times 57.6 = 172.8 \text{ W/day}$$

So, if the network is expected to operate, say for 90 days, before the battery in the uppermost sink node is replaced, then this node should be supplied with a power capacity of at least 15.55 kW. Subsequently the power requirement for other sink nodes in the network can be estimated as:

2nd tier sink node = 2 × 57.6 × 90 = 10.368 kW
Bottom tier sink node = 57.6 × 90 = 5.184 kW

Since all the sensor nodes are transmitting data packets only to the sink node at their respective tier in one hop manner therefore each sensor node may have a power requirement equivalent to that in a sink node i.e. 5.184 kW.

Let's have some feel of 'reality' on the value of P_U calculated above. P_U shows the power needed in a day i.e. 172.8W per 24 hours. This translates to 7.2W per hour (for simplicity a linear power consumption is assumed). If the node modem is powered by a typical 12V car battery then the current drained per hour would be 7.2/12 which is 0.6A. Based on a simplistic linear estimation, for 90 days (2160 hours) the current drained would be 1,296AH (Ampere-Hour).

Now, a car battery normally has a rating of 100AH. Therefore the uppermost sink node will need at least 13 (i.e. 1296/100) car batteries to support the network for 90 days operation. By the way these batteries are to be connected in parallel configuration. If the modem can be operated with a 24V 100AH source then the number of batteries would be halved. For instance the UWM1000 modem from LinkQuest Inc. [65] can be powered from 9V to 24V. Readers may refer to the link in [80] to gain further details on battery lifetime calculation/estimation.

6.6 Chapter Conclusions

This chapter presents a case study to show how the proposed 2Q algorithm may be integrated into data transmission process in an UWSN for long-term water pollution monitoring application. The UWSN adopted in this case study (cf Figure 6.2) is a static 3D architecture deployed in the form of a single chained multi-tier network with each tier having a cluster of nodes arranged in a centralized star topology. This chained-star topology appropriately formed a column of nodes to monitor a "column" of water body for pollutants in a long-term non-time critical mode.

An algorithm for data packets transmission literally termed as multi-tier TDMA scheduling algorithm was presented to show the possibility of allowing all the nodes in the network to transmit data packets without collision and channel contention. The proposed 2Q data packet size optimization algorithm was integrated into this multi-tier TDMA timing scheme. However this scheme is by no means exhaustive i.e. there are possible to evolve variants out of it. For instance, the 2Q optimization can be integrated at the end of each TDMA frame instead of at the end of each sensor node transmission. Basic TDMA time slots calculation were explained and illustrated with numerical examples.

Since the proposed 2Q optimization algorithm was developed with respect to energy efficiency therefore the sensor/sink node battery power capacity issue is being considered and discussed in this chapter. A method to estimate the battery power capacity for the sensor/sink node for the proposed UWSN architecture was described. A numerical example based on the requirements of the uppermost sink node was shown and this example was extended to illustrate how the power capacity of other nodes can be derived. Among all the nodes in the proposed network, the uppermost sink node is considered the principle node that shall determine the lifespan of the whole network. Therefore its power capacity of uttermost importance.

This chapter does pin-point a few topics/directions that could be considered by those interested readers for further research or investigations. For instance, enhancing power capacity estimation method, variants of data transmission time calculation, transmission scheme based on different network architecture/topology, etc. just to name a few.