Frame Design for a Prototype Underwater RF Electromagnetic Communication Sensor System

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***Abstract*—Electromagnetic communications in an underwater environment has been largely dismissed as impractical or impossible by researchers in favour of acoustic and optical techniques. Very Low Frequency systems do not however suffer from the attenuation experienced at higher frequencies and offer several advantages when compared to optical and acoustic methods particularly in shallow water. This paper describes the design of a flexible MAC protocol for use in a small scale wireless sensor network using VLF technology that is used to provide an underwater coastal monitoring service. The lightweight control protocol is time division based in order to fit the unique characteristics and specifications of the network. Simulations are carried out to evaluate the performances of different network scenarios with the variation of frame size.**

***Index Terms*—underwater electromagnetic communications, underwater wireless sensor networks, TDMA**

I. INTRODUCTION

The recent growing interests in monitoring aqueous environments have led to extensive research on underwater wireless sensor networks (UWSN), most of which have used acoustic waves as the physical transmission medium. Acoustics is a proven technology for underwater sensor applications with a transmission range of up to 20km [1], but it yields poor performance in shallow water where the acoustic transmission can be affected by turbidity, ambient noise, salinity gradients and pressure gradients; in addition, acoustic technology can place an adverse impact on marine life [2]. Another option that may be used for underwater transmission is optical wave, but this only delivers good performance in very clear water, and requires tight alignment due to the demand for the sight and the limitation of very short transmission ranges [3]. The latest research on optical UWSN is still ongoing such as [4].

This paper studies the design of an UWSN on the sea bed that gathers data and consequently quantifies the effects of coastal erosion beneath the sea surface. Electromagnetic (EM) waves will be used as the communication medium, of which its capabilities have been re-evaluated in [5]. EM signaling, coupled with digital technology and signal compression techniques, has many advantages that make it suitable for niche underwater applications. Comparing to acoustic and optical wave technologies, radio frequency (RF) EM technology allows flexible deployment of underwater wireless sensor network for coastal monitoring applications, where there is a high level of sediment and aeration in the water column. First, both acoustic and optical waves cannot perform smooth transition through air-and-water interface. EM waves can cross water-to-air or water-to-earth boundaries easily; its signal follows the path of least resistance, where both air and seabed paths can extend the transmission range. Second, EM transmissions are tolerant to turbulence that are caused by tidal waves or human activities, as opposed to the case of acoustic and optical waves. Third, EM waves can work in dirty water conditions, while optical waves are susceptible to particles and marine fouling. Fourth, EM operation is also immune to acoustic noise, and it has no unknown effect on marine lives.

Section II describes briefly the system implementation and network scenario. Section III explains the approach of the designated network protocol. Section IV uses network modeling and simulations to analyze the issues addressed in the previous sections, and Section V concludes the paper.

†Dr. Ian Wells, Dr. Xianhui Che, Gordon Dickers, Dr. Xiaochun Gong are both in Faculty of Applied Design and Engineering, Swansea Metropolitan University, United Kingdom. Email: {xianhui.che; ian.wells; gordon.dickers; xiaochun.gong}@smu.ac.uk. *Dr. Mark Rhodes is with Wireless Fibre Systems in UK. Email: mark@wirelessfibre.co.uk.

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II. REVIEW OF UNDERWATER RF COMMUNICATION

The recent growing interests in monitoring aqueous environments have led to extensive research on underwater wireless sensor networks (UWSN), most of which have used acoustic waves as the physical transmission medium. Acoustics is a proven technology for underwater sensor applications with a transmission range of up to 20km [1], but it yields poor performance in shallow water where the acoustic transmission can be affected by turbidity, ambient noise, salinity gradients and pressure gradients; in addition, acoustic technology can place an adverse impact on marine life [2]. Another option that may be used for underwater transmission is optical wave, but this only delivers good performance in very clear water, and requires tight alignment due to the demand for the sight and the limitation of very short transmission ranges [3]. The latest research on optical UWSN is still ongoing such as [4].

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III. System and Network Design

Coastal erosion is becoming a more common and destructive process. Data to attempt to understand this phenomenon has largely been obtained by observations and measurements of exposed coastal areas such as beaches to quantify the effects of coastal erosion. While these studies have revealed lots of important information (e.g. by determining empirical formulae for estimating the depth of closure) the details of what was happening below the sea's surface has not been remotely measurable. This means that we have only a partial picture of coastal erosion because of the absence of this important data.

Engineers have classically modeled the submerged beach profile by describing two different zones: near shore zone and offshore zone. The near shore zone is active while the offshore zone is inactive with respect to the movement of sediment, silt, sand etc. The dividing contour between these zones is known as the depth of closure. This contour and its movement is important to measure since it would give very useful data regarding the dynamics of sedimentary movement on the sea bed and enable more accurate measurements of coastal erosion.

A. Network Scenario

A small scale wireless sensor network has been designed with a fixed topology as shown in Fig. 1. The fundamental purpose of this sensor network is to find the depth of closure and the movement of seabed sediment around this contour. It will only be necessary to monitor sea bed movement below the low tide line and the sensors would need to be positioned either side of the closure contour, as shown in Fig. 1. This will enable a temporal picture of sedimentary movement around this contour to be constructed.

As in most other wireless sensor networks, this network scenario follows multiple sources and single destination traffic patterns. The data delivery is carried out by cycles. Within each cycle, after the data-gathering period, all nodes stay in sleeping mode until a scheduled transmission is initiated, and then the nodes will wake up and be ready for communication. Once data transmission is complete, the nodes will revert back to sleeping mode. The distance between every two adjacent sensor nodes is set to the effective transmission range - 40m, which means any nodes beyond the next-hop radius will not receive any data from the source node transmission. All the sensor nodes are fixed in static locations by buoys and ballasts under the water surface. In order to reduce the bottleneck transmission problem as investigated in [9], the sink node is placed in the center of the network which is above the water surface and maintains 40m distance to the next-hop sensor nodes (i.e. 2 and 5).

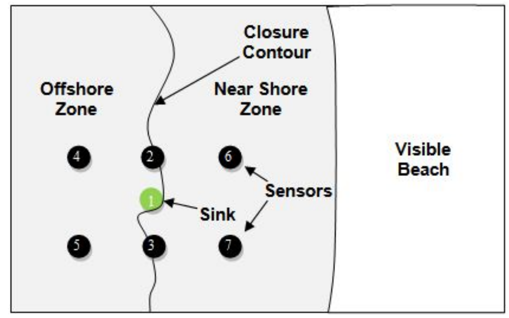


Fig. 1. Scenario of a small scale sensor network

B. Sensor Nodes

In order to quantify coastal erosion, the primary role of sensors will be to either directly or indirectly measure the movement of sea bed sediments [6]. The sensor nodes are fixed and are capable or determining the amount of sediment that is settling on top of them using a differential pressure sensor (future systems may also incorporate other measurements such as flow, turbidity etc). The system can be deployed for many months and so can build up a detailed profile of the movement of sediment at many positions on the sea bed. Sensor data is typically gathered at 2 hour intervals and is then stored locally. Typically once per day all the nodes will transfer their collected data across the sensor network to the sink node.

All measurement data will be sent to one destination node (i.e. the sink) on the shore or at any other position. The sink will be enabled with the function of Global System for Mobile communications (GSM) which allows all the collected data to be eventually transported to a central office for processing. This enables the remote collection and processing of the data. The system will also gather data regarding the health of the sensor nodes which will also be accessible by the user so enabling the failed nodes to be replaced as needed.

Fig. 2 briefly shows the structure of the sensor nodes and the sink. Each node is battery driven. The communication between sensor nodes will be multi-hop based. In order to ensure the delivery of optimized quality of signals, experiments and measurements have been carried out in [7] to determine the following communication settings. Very low radio frequency (3kHz) is used to give a 40m effective transmission radius, of which the achievable data rate is 100bps. A radio modem called Seatext [7] is employed to offer high-tolerance communications through water, air and ground. As the modem is locked to a single frequency, the transceiver needs to be implemented in a half-duplex pattern.

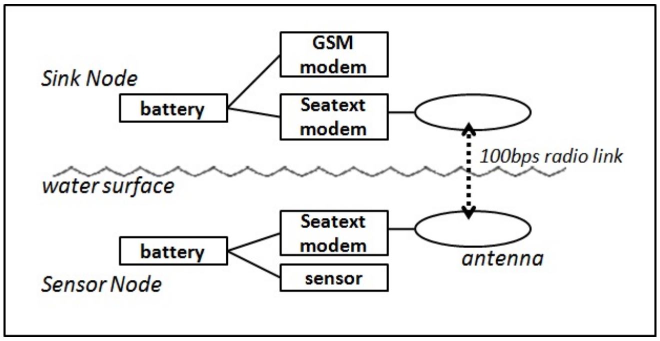


Fig. 2. Schematic of the sensor node and the sink

According to [5], magnetic coupled loop antennas are the most compact practical solution for duplex submerged systems, which is built into the designated system. Loop antennas are directional in nature, which can be exploited to allow selection of a single propagation path. Alternatively Omni-directional antennas can be implemented by crossing two loops so that their planes intersect at right angles. Even though larger loop area gives greater antenna gain, practical systems can be designed using relatively compact loops.

An even driven operating system called Contiki is implemented on individual nodes in the wireless sensor network [8]. The Contiki operating system has several features which are attractive to sensor network developers including a small memory footprint. It is open source based and provides both full IP networking and low-power radio communication mechanisms. For communication within a wireless sensor network, Contiki uses the lightweight Rime low-power radio networking stack [8]. The Rime stack implements sensor network protocols ranging from reliable data collection and best-effort network flooding to multi-hop bulk data transfer and data dissemination. IP packets are tunneled over multi-hop routing via the Rime stack. Contiki is designed for microcontrollers with small amounts of memory. A typical Contiki configuration is 2 kilobytes of RAM and 40 kilobytes of ROM. Interaction with a network of Contiki sensors can be achieved with a Web browser, a text-based shell interface, or dedicated software that stores and displays collected sensor data. The text-based shell interface is inspired by the UNIX command shell but provides special commands for sensor network interaction and sensing. Contiki was chosen for this system since it offered all the functionality required within the sensor network.

C. Control Protocol Design Considerations

Networking protocol plays a vital role in saving power and providing consistent connections in underwater wireless communications, most of which have been designed for acoustic technologies [10]. Due to the unique characteristics of the designated system, an efficient and effective control protocol needs to be carefully designed to meet the network specifications and requirements.

A few issues have to be addressed prior to the network protocol design: low data rate, half-duplex communication pattern, short transmission range, and the possible contention of resources in the burst transmission period. In this project, the short transmission range issue is not a major concern due to its desirable application field. 23 permutation with 40m radius (as shown in Fig. 1) would create a plausible frontline that provides sufficient data for the coastal research [6]. The network characteristics have led to the decision of using a variation of Time Division Multiplexing Access (TDMA) as the control protocol, because it can resolve the problems addressed above. Each end sensor node will be allocated with a time slot during which it can transmit the collected data to the sink. Any involved intermediate nodes also need to wake up to relay the data. Within each time slot, the source node will follow this state transition: wake up $\rightarrow$ transmitting only $\rightarrow$ sleep; while intermediate nodes will follow this transition: wake up $\rightarrow$ receiving only $\rightarrow$ transmitting only $\rightarrow$ sleep. The above is based on the assumption that no acknowledgement (ACK) packets are facilitated in the process of communications.

There are a few advantages of using TDMA as the control protocol. First, there will be no collision between any two transmissions during the burst traffic period. The end-to-end (ETE) data delivery process for each sensor node is completed within its own time slot. Second, it fits the half-duplex transceiver mechanism. The active sensor nodes are in either transmitting-only or receiving-only mode. Third, TDMA will be used as a cross-layer control protocol which is light-weighted and efficient. Fourth, while one sensor node is transmitting data, all the uninvolved sensor nodes can stay in the sleep mode in order to conserver battery life.

IV. TDMA Frame Design

A. Frame Structure

At the top level the system uses a flexible TDMA method of allocating time slots to each node in the network as a data collision avoidance mechanism. The flexibility comes from the ability of the system to redefine the size of the time slots as desired; this capability enables the prototype system to experiment with different settings to obtain optimum settings.

The transmissions of all the nodes in the network including the sink are allocated a time slot during which the node in question transmits and all other nodes listen. The total time taken for all nodes to go through a transmission phase is called the TDMA Data Frame. The frame therefore is constructed from the time slots allocated to the nodes. In order for the system to function correctly all nodes must have a synchronized clock or the slots will be incorrectly aligned and so a clock synchronization protocol will need to be employed to make sure that synchronization is maintained. Even with a good synchronization protocol there will still be some drift of the clocks between the various nodes and to allow for this problem a guard band is placed between all the time slots to allow for this problem.

Synchronization of the clocks will need to take place via a synchronization frame broadcast by the sink during its time slot. This will be around the time when a Set of Data Gathering Readings are transmitted.

Fig. 3 shows how this would work for the 6 node network for the prototype shown in Fig. 1. The frequency of the data

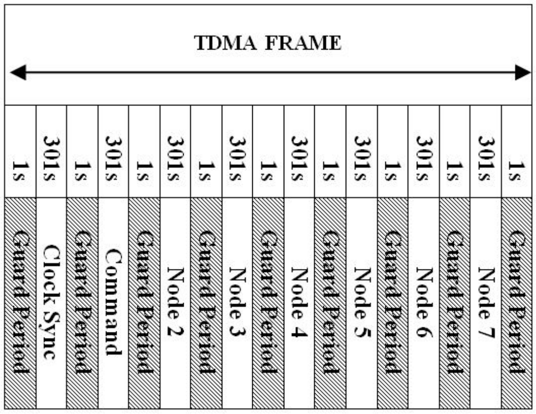


Fig. 3. TDMA Frame Structure

gathering periods relative to the time slots would depend upon the size of the time slots.

The data transmission is enabled with Reed Solomon (RS) (255, 233) Forward Error Correction (FEC) [11], which sets 255 bytes as the maximum size of the data frame for each time slot. The following shows the calculation of the time needed to transmit data around the network. These calculations allow for a single pressure sensor where a single frame containing all the data from a set of data gathering periods is transmitted once this set has been filled with data.

From Table I we have 2128 bits in the complete frame including all physical layer information while the data rate will be at 100bps (bits per second) as mentioned in Section III. One frame can contain 21 data readings and so if we only have pressure sensor readings along with the associated time stamp then the time to transmit once frame is 21.28 seconds. If we were to transmit one frame for each node then for our prototype system with 6 nodes the total time needed would be as follows assuming that a maximum distance would need to be traversed through the system.

We used a simple DATA and ACK method of transmission, where each data frame requires an acknowledgement frame to signify successful receipt. This will involve a data frame of 2128 bits followed by an ACK of 124 bits. If we allow for 3 failures, we could have 4 Data Frames (2128 x 4 = 8512 bits) and one ACK frame (124 bits). The total number of bits that would need to be transmitted would be 8636 bits. This would take a time of 8636/100 = 86.36 seconds or approximately 87 seconds add an overhead for processing and take 88s for the rest of the calculations.

We also need to add the time that we must wait after each Data Frame has been transmitted; this value (which is calculated below) is 3 s. This will almost add 3 x 3 = 9 s (1 ACK is allowed above), it is actually slightly less than this since the last successful data transmission would take a little less than 3 s (2.24 s). Since the actual time could be a tiny amount less than 3 s then it has been rounded up. We assume therefore that in the worst case in order to get a single frame across each link will take 88 + 9 = 97s which is rounded to 100 s. The maximum number of hops is 3 and so the maximum slot size will be 3 x 100 = 300 s.

TABLE I
NUMBER OF BYTES/BITS IN A DATA FRAME

Description	Size (bytes/bits)
Size of payload	255/2040
Size of Physical Layer Fields	11/88
Size of payload + physical layer header + Preamble	266/2128

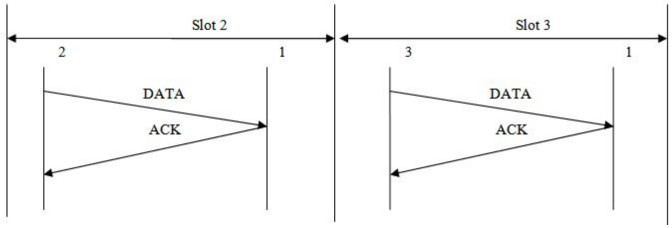
The calculations have not taken into account the Guard Period calculation and this will be done next: The nodes will lose 1 μs in every second, so after 12 hours (the minimum period for data transfers) they will lose 12 x 60 x 60 x 1 x 10^{-6} = 0.0432 s. Since the drift could be either negative or positive relative to each node then the maximum time drift in a set of data gathering periods would be twice this value i.e. 0.0864 s. Allow a little more than and we should have a Guard Period of 0.1 seconds. For the maximum data gathering period of 36 hours then the figure would be 3 times larger at 0.3 seconds. As can be seen from the above calculations this is almost negligible in relation to the total frame size so allowing for 0.3 seconds the larger value would not have major implications.

If we make all the TDMA slots the size of the largest slot needed then we would have slots of length 300 seconds with 0.3 second guard bands between them. It is also prudent to allow some extra time for the processing time and so if we round the time for a slot to 301 s allowing for 1s guard bands either side; this is sufficient to allow for these times. Obviously these times have been rounded up in most cases and the actual values are likely to be less than these calculations. This was a major reason why the prototype system was designed to be flexible with regard to the setting of these values. If we continue with this scenario then the TDMA Frame is (301 x 8) + (1 x 9) = 2417s = 40.28 minutes as shown in Fig. 3.

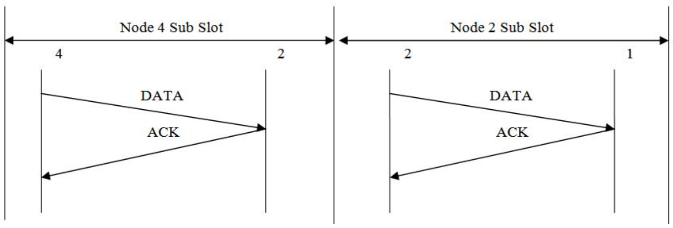
These long time periods are far larger than we would normally expect in an air based communications system which underlines why modified techniques were needed for the undersea network to function correctly. Functioning of the TDMA Timeslots is explained in detail in the following example.

The function of time slots 2 to 7 is to get its Data Frame to the sink node 1 and so node 1 will be in receive mode for most of this time. Consider the example of the events that will take place in slot 2. Node 2 will need to get its own data to the sink. During time slot 2 only node 1 (the sink) needs to communicate and so nodes 3, 4, 5, 6 and 7 will be powered down. During time slot 3 only node 1 (the sink) needs to communicate and so nodes 2, 4, 5, 6 and 7 will be powered down. Fig. 4(a) illustrates the sequence of events during slot 2 and 3.

Since the nodes are half duplex they will need to switch between LISTEN and TRANSMIT mode as is necessary during the slot. At the end of this process node 1 will have received the data from both nodes 2 and 3. Assuming that all nodes are functioning then Fig. 4(b) shows what will happen for node 4's TDMA Slot. There are two further sub slots within



(a) Slot 2 and 3



(b) Slot 4

Fig. 4. TDMA Slot Details

slot 4 to enable the data to propagate from node 4 to node 2 and then to node 1. The number of sub slots will be determined by the routing algorithm so if for instance node 2 was dead then the route would be 4 to 5 to 3 to 1 and so the TDMA slot would then need 3 sub slots. The size of the fixed size TDMA frames correspond to this maximum hop as calculated earlier.

Another consequence of this process is that all nodes that may be possible routes from 4 to 1 need to be switched on but others can be switched off. Hence for node 4's TDMA slot nodes 1, 2, 3, 4 and 5 need to be switched on and nodes 6 and 7 can be switched off. Table II shows which nodes can be switched on or off during the TDMA slots.

At the beginning of every data transmission period the TDMA Clock Sync Slot will be used to run the clock synchronization process which is not detailed in this paper. This is followed by the Command Frame Slot where new configuration information which has been defined by the Application Software is distributed around the network nodes. The Command Frame structure has been previously defined.

Dynamic routing has not been implemented on this prototype system but will be implemented in future commercial versions. Consequently all possible routes are pre-programmed into the system. In this simple network most nodes have only one possible route and some have 2 possible routes. If the choice of the preferred route fails then the alternative route will simply be chosen by the node.

The timer period calculation is the time that a node will wait after transmitting a frame before retransmitting. This value needs to be as large as the worst case delay across a link which is: Time for the node to process the frame + Time for the ACK to be transmitted = 1 + 1.24 = 2.24 which can be rounded up to 3 s to give a bit of slack. This value is the same regardless of the frame type that is transmitted and is needed to calculate the countdown timer time needed when a data frame is transmitted and so we have initially set this to a value of 3 s at deployment. To ensure that the data transmission period is completed between the measurement periods we need to start

TABLE II
NODES SWITCHED ON OR OFF DURING TDMA SLOTS

Slot Number	Nodes switched ON	Nodes switched OFF
2	1,2	3,4,5,6,7
3	1,3	2,4,5,6,7
4	1,2,3,4,5	6,7
5	1,2,3,4,5	6,7
6	1,2,3,6,7	4,5
7	1,2,3,6,7	4,5

the data sampling after an initial delay of 1 hour starting from receipt of the first command frame. This will make sure that all data gathering time periods are at least 1 hour away from a transmission time slot.

B. Data Frame Format

The sensor data is transported around the network by means of a Data Frame the format of which is described in this section. A detailed view of the frame structure is shown in Fig 5. Physical layer header is not shown from now on. The Physical Layer Preamble is a requirement of the physical layer of the communication link as is the Physical layer header.

A simplified addressing scheme is used where each sensor node will have a 2 part addressing scheme each using 8 bits, as is used with networkable protocol addressing schemes such as IP and IPX. These addresses are carried in the physical layer header and must be extracted before this header is discarded. This is done to simplify the number of fields that are used in the frame as a whole which consequently leads to the cross -layered approach described.

This selection of addressing will therefore allow 256 possible separate networks of sensors each containing up to 254 separate sensors. This will cover any expansion of the system that may be planned in the future. The network field is indicated by 'dest net addr' field for the destination address and 'src net addr' field for the source address as shown in figures 9 and 10. These fields perform the function of the network portion of the IP address in traditional networks.

The frames' data payload is made up of 1680 bits. Each sensor reading has three parts consisting of 2 x 32 bit pressure readings from the differential sensor and a 16 bit time stamp i.e. 80 bits in total. The frame can therefore accommodate 1680/80 i.e. 21 readings. There are 4 possible data sampling rates either every 2, 4, 6 or 8 hours and 3 data transmission periods of 12, 24 or 36 hours. Each frame can take 21 readings. Table III summaries what this will mean for the system.

Since most data frames are only partially filled then we have developed a zero data padding strategy where if the data frame is not completely filled then we transmit the partially filled frame with all headers etc present. At the receiver the frame would be expanded to its full 255 byte size by infilling spare frame capacity with zeros. This will enable the RS(255,223) FEC algorithm to still be used for error correction. The remaining fields within the frame are described below:

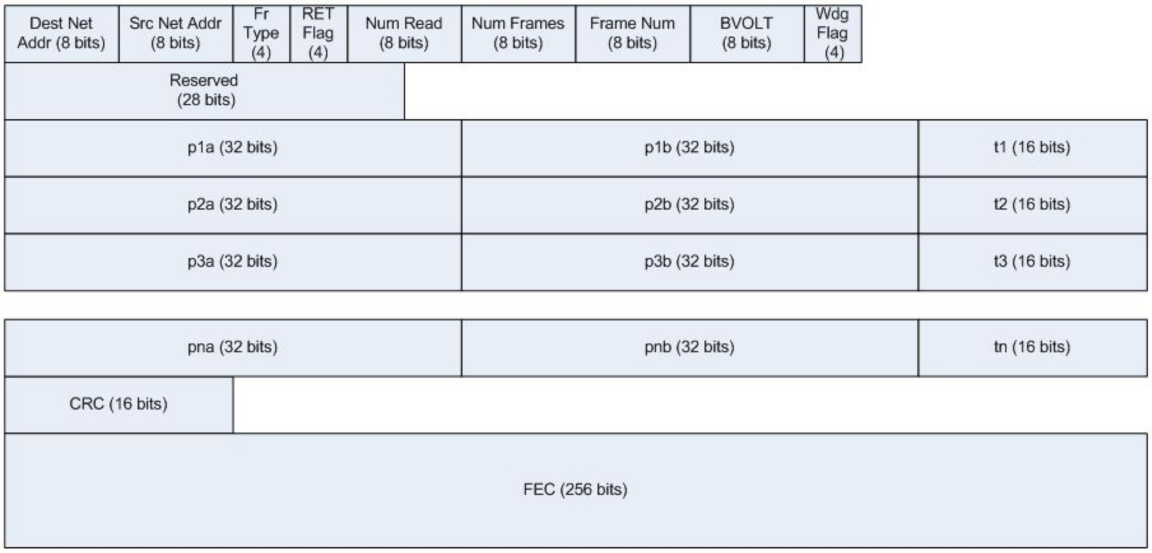


Fig. 5. Detailed Data Frame Structure

TABLE III
DATA GATHERING AND TRANSMISSION PERIODS

Data Gathering Period (hours)	**Data Transmission Period (hours)**	**Number of Readings**
2	12	6
2	24	12
2	36	18
4	12	3
4	24	6
4	36	9
6	12	2
6	24	4
6	36	6
8	12	1
8	24	3
8	36	4

- ’num readings’ field indicates the number of sensor readings contained in the payload of the frame,
- ’crc’ field contains CRC information for the frame (but not the physical layer header)
- ’FEC’ field is used for FEC (Reed-Solomon (255,223) the entire frame is used apart from the preamble of the physical layer and the physical layer header. Note that the use of FEC is indicated by a flag in the physical layer header.
- ’num frames’ contains the number of frames that are to be transmitted
- ’frame num’ is the frame number in a set of frames that are to be transmitted
- ’Fr Type’ defines if the frame is of type DATA, COMMAND, ACK etc
- ’RET Flag’ indicates the number of retries that a frame has so far taken to cross a link (this field could be used to monitor the health of the links)
- ’BVOLT Field’ logs the battery voltage of the node for health monitoring purposes
- ’Wdg Flag’ is a field that is set if the watchdog timer has rebooted the node since the last data transmission.
- The reserved field is unused and may be used for future expansion. The reserved field will not be transmitted it will be omitted and reconstructed using the zero padding scheme mentioned elsewhere.

The length of the frame can be obtained from the ’Phy Frame Length’ field in the physical layer header; this must be extracted before the physical layer header is discarded during the de-encapsulation process. The Data Frame will have a value of 0000 (0) in the Fr Type (4 bits) field to distinguish it from the other frame types on the network.

C. Command Frame

The system will need additional frames that do not carry data but carry command and control information. Since the network uses TDMA slots then pre-overhead frames will not be needed since the frame structure will itself be used to prevent data collisions. The network will use a simple communications method. A Data Frame is transmitted followed by an ACK when the data is successfully received.

The Command Frame is used to initialize most of the functionality of the sensor network and this is the mechanism used to keep the network as flexible as possible. It is able to initialize the following features:

- The codes for Data Gathering Period (DGP) of 2, 4, 6, and 8 hours should be 0000, 0001, 0010, and 0011 respectively.
- The codes for Data Transmission Period (DCP) for 12, 24, and 36 should be 00000000, 00000001, and 00000010 respectively.
- Number of data transmission retries which is defined by using the Ret Field.

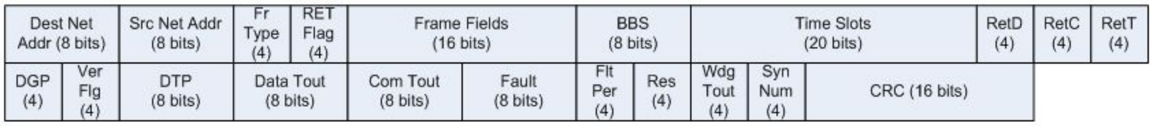
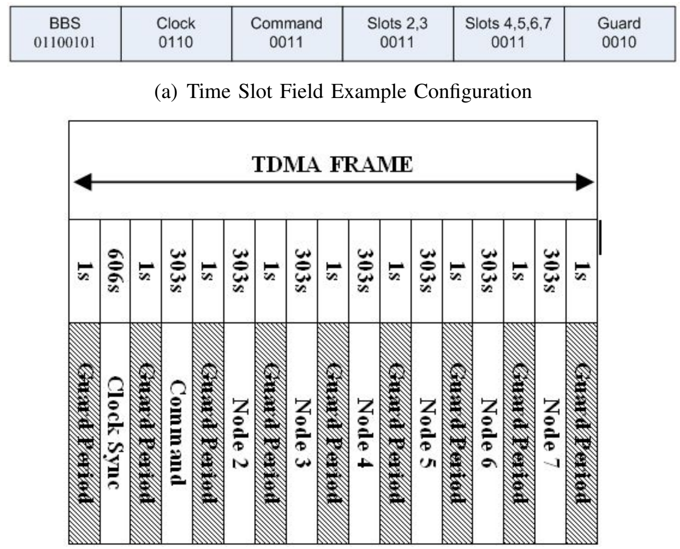


Fig. 6. Command Frame

- ’RetD field’ defines the number of retries that a DATA frame will attempt when the frame fails to reach the destination. This field will be determined by the application software and configured from the initial configuration command frame that is sent before the data gathering period. This field is only needed in the Command Frame and is not present or not used in other frames.
- ’RET Flag’ indicates the number of retries that a frame has so far taken to cross a link. This field could be used to monitor the health of the links.
- ’Fr Type’ defines if the frame is of type data, command, ACK etc.
- A Special Command Frame will initially be sent to enter Network Verification Mode, Network Verification Mode will be exited upon receipt of a normal Command Frame during the next available Command slot in the TDMA Frame.
- The Command Frame number of retries to nodes other than from sink to first node can also be set using the ’RetC Field’.
- The Time Synch Frame number of retries can also be set using the ’RetT Field’.
- In order to allow timely network verification on deployment a Network Verification Mode will be configurable. Dummy data frames that carry no payload will be immediately sent to the sink to test that the network is functional the Dummy Data Frames will be identified by using a value of 0011 (3) in the Frame Type field. Network Verification Mode will be entered by sending a Command Frame with the Ver Flag set to 0001. The Ver Flag will normally have this flag set to 0000 for all other frames.

The Command Frame does not have a FEC facility but will be retransmitted indefinitely by the Application Software until an ACK is received from the sink node. Other nodes could have a default of 4 retransmissions as with the Data Frame. The Command Frame is shown in Fig. 6. It is identified since it uses a value of 0010 (2) in the Frame Type field. The frame size is 152 bits + 88 bits from the physical layer giving 240 bits in total; the reserved field has been added to allow for any potential expansion in the future.

The ’Time Slots’ field, as shown in Fig. 6, is a special field that allows the set up of the TDMA frame. The start of each time slot will be a relative time value that is used by the nodes. Eight relative values are needed to define the start times of each of the time slots. The time slot sizes are determined by defining a smaller Building Block Size (BBS) which is 8 bits in size. The other slots are then defined relative to this using the ’Time Slots’ field. Each time slot will begin after a



(a) Time Slot Field Example Configuration

(b) Example TDMA Slot Configuration

Fig. 7. Example configuration for Time Slot field

multiple of the BBS time value.

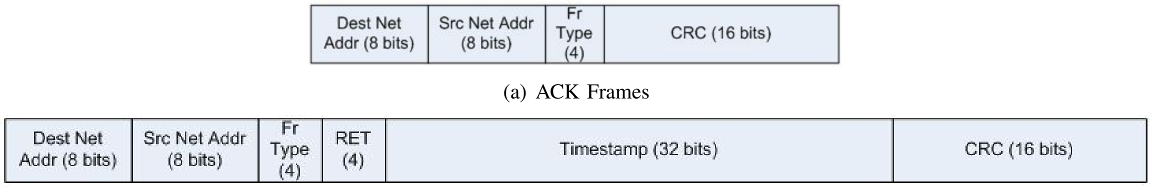
The Time Slots field consists of 4 bits Clock field, 4 bits Command field, 8 bits Slots field, and 4 bits Guard field. Each sub field defines the multiplier used for the building block time found in the BBS field. The Guard sub field defines the size of the guard bands in 0.5 second blocks. These features are best explained by an example. For instance if the ’Time Slots’ field had the entries shown in Fig. 7(a), with a value of 101 seconds (011001012) in the BBS field, and a guard band of 1s (2 (i.e. 00102) x 0.5), then this would produce a TDMA Frame with the slot sizes shown in Fig. 7(b).

This facility allows experimentation with different slot sizes when the system is operational. The Command Frame will upon initial network configuration contain all the fields as indicated in Fig. 6. It would however be wasteful of bandwidth if all the information was contained in all the subsequent Command Frames. Consequently the number of fields present in a command frame can be specified by the ’Frame Fields’ field. There are 16 bits in the ’Frame Fields’ field, each of which represents a field in the frame. The bits are switched on (’1’) or off (’0’) to represent the presence.

D. Other Frame Types

The other frame types are Acknowledgement Frame (ACK), and Time Synchronization Frame.

1) ACK Frame: The Acknowledge (ACK) frame is sent as an acknowledgement to a transmitting node when a data frame has been successfully received.



(a) ACK Frames

(b) Time Synchronization Frames

Fig. 8. Other Frame Types

The frame is very simple, as shown in Fig. 8(a), and it uses a value of 0001 (1) in the Frame Type field. It is only transmitted once and so if it does not get received then this will initiate another retransmission of the Data Frame. The frame size is 36 bits + 88 bits from the physical layer giving a total of 124 bits.

2) Time Synchronization Frame: The suggested time synchronization scheme is loosely based on the Delay Measurement Time Synchronization (DMTS) method, which has been proven to be highly energy efficient and computationally lightweight since it requires only one time broadcast to synchronize all the nodes in a network [12]. Before the slot transmission commences, a one way message will be propagated to all sensor nodes which will compare the remote and the local time stamps to obtain the line of best fit.

The clock synchronization algorithm needs to use a special 'Time Sync' Frame which is identified since it uses a value of 0100 (3) in the Frame Type field. In order for the TDMA structure to accommodate multiple time stamp transmissions, it is important that the time synchronization frame is as small as possible. The frame structure is shown in Fig. 8(b).

The key to the flexibility of this system and something that is novel in this research is the ability to define virtually every parameter of the TDMA frame structure. This flexibility is achieved by using the Command Frame as detailed in this section. The Command Frame has the ability to change these parameters during the Command time slot as shown in the TDMA diagram of Fig. 5.

V. Evaluation and Analysis

In order to deliver efficient and effective performance, the network protocol should account for the following parameters: delay, battery consumption, throughput, and so on. Based on the scenario illustrated in Fig. 1, a network has been modeled and simulated with OPNET Modeler [13], within which the original source codes for propagation delay model (*dra_propdel.ps*), transmission delay model (*dra_txdel.ps*) and power attenuation model (*dra_power.ps*) have been altered to simulate underwater EM communication environment. The system is set up according to the network specifications, as shown in Table IV. Each sensor node should have four states: data-gathering, transmitting, receiving, and idle (i.e. sleeping). The power consumption for each state is either measured or estimated on the actual node system, except for the data gathering state which is estimated to be negligible hence is excluded in the simulations.

As for the packet size, three configurations are chosen: 2040 bits (maximum data payload), 1100 bits (half size data payload), and 360 bits (no data payload, header only). The hypothesis was that the bandwidth cost for the overheads will lower down the network efficiency, hence we should maximize the data payload size in order to achieve high network goodput. Table V shows the goodput for three different scenarios, which implies that as long as data payload occupancy is over 50% of the field, the network will deliver acceptable efficiency (i.e. more than 76% goodput).

TABLE IV
SIMULATION SETUP PARAMETERS

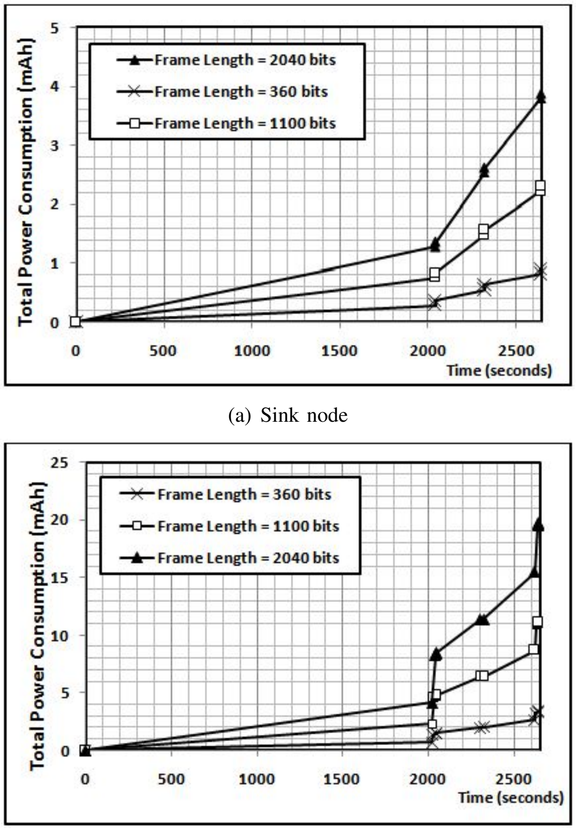
Data Tx/Rx Rate	100 bits/second	
Time Slot	300 seconds	
Burst Inter-arrival Time	2000 seconds	
Power Consumption Rate	Tx State:	520 mA (measured)
	Rx State:	210 mA (measured)
	Idle State:	0.2 μA (estimated)

TABLE V
GOODPUT

Packet Size	Goodput
360	0%
1100	76%
2040	82%

Battery usage is an important performance parameter in the UWSN, which indicates the energy efficiency of the network protocol. Fig. 9 shows the total power consumption of the sink and an intermediate node (node 2 or 3 in Fig. 1) for one TDMA cycle. Based on the comparison between Fig. 9(a) and 9(b), the intermediate node consumes more power than the sink node which was not expected. The explanation for this occurrence follows. Even though the sink node needs to stay awake for each time slot, the power for receiving data is much lower than the power needed for sending data. On the other hands, the intermediate nodes need to be engaged with the transmission states three times in a TDMA cycle: one time to transmit its own data, and two times to relay its neighbor's data. Hence the overall power usage for the intermediate nodes will exceed the one for the sink.

Fig. 9(a) and 9(b) also compare the power usage for different scenarios - long, medium, and short data packet size. The statistics indicate that longer data payload results in more battery usage; however the increase of data payload size does not remarkably affect the power consumption of the sink node, in other words, the difference between minimum



(a) Sink node

(b) Intermediate Node

Fig. 9. Total power consumption for one cycle

and maximum scenarios of data payload size is minimal. The excessive increase of power consumption of intermediate nodes is substantial, which will impose limitations on the battery deployment.

Assuming that a compact and low-cost 18Ah battery is employed for each node, and that two cycles of readings will be sent daily, the battery capacity will be able to maintain the network for approximately one year. This demonstrates a plausible deployment of the designated system.

All the data can be effectively delivered to the sink since no node failure is simulated. Table VI measures the End-to-End (ETE) delay of all the nodes for different scenarios. The ETE delay includes the point-to-point transmission delay and the waiting time prior to the transmission. The waiting time consists of the duration for synchronization and command frames to cross the network, as well as the pending time for the allocated slot. The results indicate that the total networking time for one cycle transmission lasts roughly half an hour. The variation of frame size does not cause significant fluctuation of network delay, since the delay is counted with the unit of minutes in the project context.

TABLE VI
ETE DELAY (SECONDS)

Packet Size	Node 2	Node 3	Node 4	Node 5	Node 6	Node 7
360	307.2	603.6	907.2	1207.2	1503.6	1807.2
1100	322.0	611.0	922.0	1222.0	1511.0	1822.0
2040	340.8	620.4	940.8	1240.8	1520.4	1840.8

VI. CONCLUSION

A small scale underwater wireless sensor network is designed to employ RF electromagnetic communication of which the capabilities have been re-evaluated in previous research. The network has a multi-hop static topology for coastal monitoring purposes which will work under shallow water conditions. TDMA is chosen as the control protocol for the half-duplex pattern communication network. This paper described the details of the MAC layer protocol and the use of a flexible TDMA framing technique that was used to gather the data from the prototype sensor network. The basic aim of designing the prototype was to maintain as much flexibility as possible because of the many unknowns in the hostile deployment environment. This we believe has been achieved by the use of the flexible Command Frame design. The analysis of the simulation results has led to the conclusion of feasibility and effectiveness of the designated system and network architecture. Future research should further explore the different aspects of network performance, such as scalability, necessity for reliable transmission, and comparing the chosen protocol with other potential options.

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