Multi-Coil MI Based MAC Protocol for Wireless Sensor Networks

Niaz Ahmed, Yahong Rosa Zheng, David Pommerenke
Dept. of Electrical & Computer Engineering
Missouri University of Science & Technology, Rolla, MO 65409
{namn3, zhengyr, davidjp}@mst.edu

***Abstract*—Medium Access Control (MAC) protocol is an important metric of wireless sensor networks because of its high impact on network performance. This paper proposes an energy efficient MAC protocol that can be used for both terrestrial and underwater wireless sensor networks. The state transition diagram has been presented in the paper and current consumption for each state has been recorded to evaluate the energy efficiency of the proposed MAC protocol.**

I. Introduction

Medium Access Control (MAC) protocol is an important quality metric of terrestrial and underwater wireless sensor networks. An inefficient MAC layer can result in heavy packet collisions, delayed communication and significant energy wastage. Wireless sensor networks offer a number of challenges for real time MAC layer protocol implementation and the major challenge is energy consumption [1] because most of the wireless sensor networks applications require deployment of sensor nodes with limited energy resources . The challenge becomes more severe with slow speed of propagation, low data rates and high processing power requirement in case of underwater acoustic sensor networks [2].

During recent years researchers have proposed a number of energy efficient MAC protocols for both terrestrial [3]–[15] and underwater wireless sensor networks [16]–[24] but unfortunately, only a few techniques have been prototyped as testbeds. We believe that real time implementation of the MAC layer for wireless sensor networks is a real need and propose a contention based MAC protocol with magneto-inductive(MI) based communication.

In this paper we present the proposed energy efficient MAC layer protocol for wireless sensor networks. The sensor node is capable of magneto inductive communication which allows the sensor node to be deployed for both terrestrial and underwater sensor networks [25]. This paper present the design decisions, state transition diagram and implementation details of the proposed MAC layer.

II. Our Design Rationale

The primary goal is to design an energy efficient MAC protocol for a sensor node in wireless sensor networks. Our goal stems from the fact that monitoring applications require the sensor node to run for long time without replacing the battery power. We chose to use MI communication that allow the sensor node to work both in terrestrial and underwater wireless sensor networks.

TABLE I
Common Sources of Energy Consumption

Idle Listening	When the sensor node is listening to the channel in order to receive an upcoming packet
Packet Collision	When two or more nodes start to communicate simultaneously and result in collision of the simultaneously transmitted packets.
Packet Overhearing	When a sensor node receives and tries to decode a packet that is not destined for it.
Control Packet Overhead	When a sensor node include additional control information to the actual payload.

Table I shows the common sources of energy consumption for a MAC protocol. All these sources contribute in energy losses in an idle mode when the sensor is listening to the channel. To keep the sensor node to consume the minimum possible energy in these cases we:

- Isolate the power of each component in the sensor node design. This allows the sensor node to shut down the components that are inactive. The software controls the power to each component and decides if the component needs to be ON/OFF. This significantly reduce the overall power consumption of the system.
- Sense the channel for the carrier before transmitting a packet and at the same time exploit the directional nature of MI communication to avoid collision.
- Keep three separate packet types of different length to lesser the overhead bytes.

III. Proposed MAC Algorithm

Figure 1 shows packet exchange information between two nodes: source and destination. The source initiates the communication by sending a reservation packet (REV) to the other node. As MI coils are directional and depend heavily on transmit & receive coil's orientation, the sensor node uses three dimensional coil for reliable and omni-directional communication. It is to be noted that the sensor node uses all the three coils to listen to the channel but use only one of the three coil to transmit at a given time. Thus the same REV packet is being sent three time from each of the three coils of the sensor node.

After the packet reaches the destination, the receiver sensor node compares the received packet sent by the three coils and

978-1-5090-1537-5/16/$31.00 ©2016 IEEE

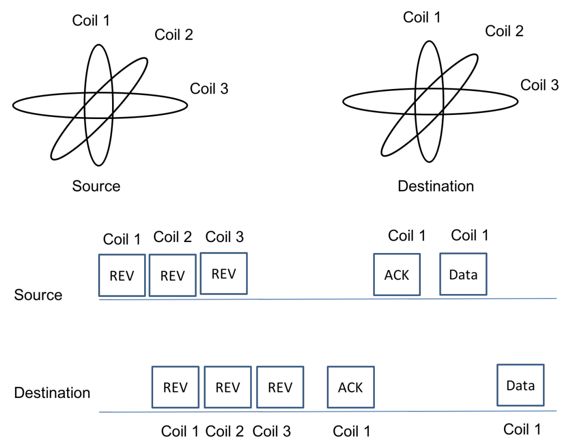

Fig. 1. Packet exchange information between source and destination when initiating a communication

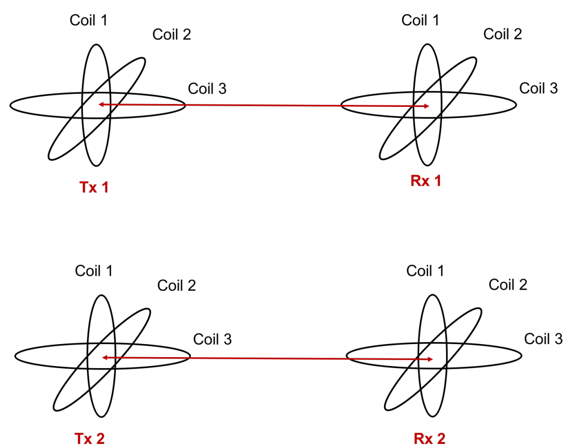

Fig. 2. Two nodes can simultaneously transmit data packets to other nodes if the strongest coil pair is different.

records the coil pair that receives the strongest signal. The acknowledgment packet (ACK) is then sent back by using the coil with strongest RSSI. The two nodes then use the selected transmit & receive coil pair for further communication.

The directional nature of the MI coils and using the strongest transmit receive coil also allow nearby nodes to communicate with each other. Figure 2 shows a simple case where Tx1 & Rx1 communicates with coil 1 being the strongest coil and Tx2 & Rx2 also communicates with coil 2 being the strongest coil.

A. State Transition Diagram

The sensor node is programmed to remain in one of the five states: Idle, Receive, Channel Sensing, Data Acquire and Transmit states and the state transition diagram is shown in Figure 3.

The sensor node starts with initialization and enters the Idle state which is an extreme low power state. The receiver IC is the only component that is running and is listening to the channel. The sensor node remains in the idle state until there is an interrupt from the sensor or a packet is received with

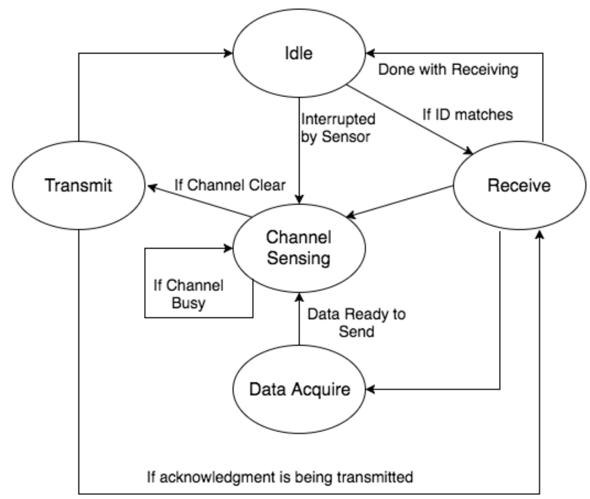

Fig. 3. State transition diagram of the proposed MAC protocol

correct ID. If an interrupt has been occurred, the sensor node prepares the transmit packet and enters the channel sensing mode. In case of the packet being received with the correct ID the sensor node enters to the receiving state.

Once the sensor node receives a packet and the ID matches the sensor node's ID, the sensor node enters the Receiving state. During this state the sensor node decodes the packet. If the received packet is a hand shaking packet, the sensor node prepares the packet to send back the acknowledgment and goes to Channel Sensing state. If the received packet is the data packet, the sensor node remains in the Receive state until the last byte of data is received. After receiving the last data packet, the sensor node goes to idle state. If the received packet requires the sensor node to transmit the sensor data, the sensor node then goes to the Data Acquire state.

In the Data Acquire state, the sensor node turns ON the sensors and collects the data from the interfaced sensors. The acquired data is formed into a packet and sensor node goes to Channel Sensing state.

The Channel Sensing state is the important state and key part of the proposed MAC protocol. Whenever a packet is being ready to be transmitted, the sensor node enters the Channel Sensing state. During this state the sensor node senses the channel to see if the channel is busy or available. The sensor node remains in the Channel Sensing state if the sensor node detects a nearby carrier and will go to Transmit state only when the channel is available.

During the Transmit state, the sensor node turns ON the transmitter circuitry and sends out the packet. If the transmitted packet is hand shaking packet, the sensor node goes to the Receive state as the sensor node expects an acknowledgment. Other than hand shaking packet, the sensor nodes enters the Idle state after the packet is being transmitted.

B. Packet Types Used

Figure 4 shows the three different types of packets used in the proposed MAC layer: Reservation packet (REV), Acknowledgment (ACK) and Data Packet. All the three packets start with one byte carrier letting the receiver sensor node to set up and ends with one byte EOF which indicates the end of the packet.

REV packet is used to initiate the communication between the two nodes. This is the hand shaking packet where the source sends a 13 byte packet. The carrier byte is followed by a one byte preamble allowing the receiver sensor node to start decoding the target ID. The preamble is then followed by a four byte target ID which the sensor node compares with the programmed ID and will forward the rest of packet only if the ID matches. If the ID does not match the packet is dropped by the sensor node. The next byte is the packet Id which identify whether the packet is REV, ACK or Data. Since the REV packet is the first packet of the transmission the sensor node includes the one byte transmit coil information. The purpose of the transmit coil information is to let the receiver sensor node know which coil is best suited for the two nodes to communicate.

After successful reception of the REV packet, the receiver sensor node reply with an ACK. The ACK is a five byte packet starting with one byte carrier and then followed by the one byte packet ID. The ACK also includes the transmit and receive coil information that can be then used for further communication.

Once the ACK is received the two sensor nodes are ready to exchange data packets. The data packet contains the sensor data or other information need to be transmitted which can vary between 1 to 16 bytes.

Carrier	Preamble	Target ID	Packet ID	Tx ID	Tx Coil ID	EOF
1 byte	1 byte	4 bytes	1 byte	4 bytes	1 byte	1 byte

Reservation Packet

Carrier	Packet ID	Tx Coil ID	Rx Coil ID	EOF
1 byte	1 byte	1 byte	1 byte	1 byte

Acknowledgment

Carrier	Packet ID	Data Packets	EOF
1 byte	1 byte	1 byte – 16 bytes	1 byte

Data Packet

Fig. 4. The three packet types being used in the proposed MAC protocol

IV. Implementation details

The block diagram of MI sensor node is shown in Figure 5 and the PCB hardware is shown in Figure 6, where micro-controller is the main controlling unit. The common micro-controller families that are being used in sensor network applications are Microchip PIC family, TI MSP430 family and Atmega family. PIC micro-controllers offer ultra low power consumption whereas Atmega offers high performance. We chose MSP430 family which is better suited for applications with high performance and lower power consumption. The micro-controller we are using in our sensor design is MSP430F5529 which is 16 bit ultra low power micro-controller with 128 KB Flash and 8 KB RAM.

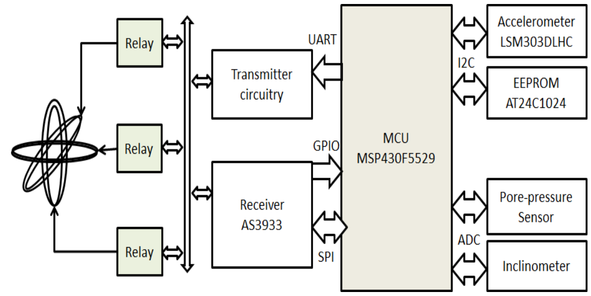

Fig. 5. Block Diagram of the low-power sensor node with MI communication and sensing capabilities

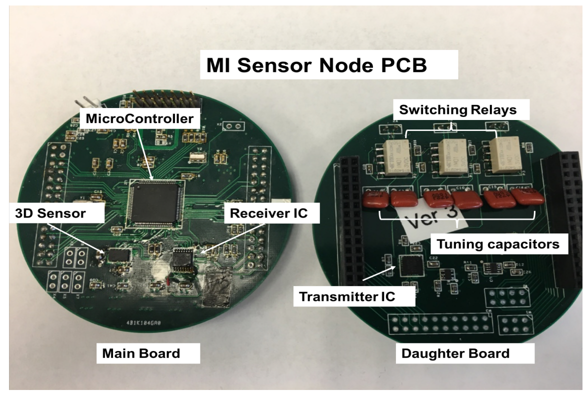

Fig. 6. Printed Circuit Board (PCB) of sensor node. Antenna coils are not shown.

The micro-controller uses the serial and ADC peripheral to interface with the other components. I2C bus is used to interface with accelerometer and memory chip. The analog sensors: pore pressure and inclinometer use the 12-bit ADC peripheral to connect with micro-controller. The micro-controller forwards the data to the transmitter IC (ATA5276) through Universal Asynchronous Receive and Transmit (UART) port. The micro-controller communicates with the receiver IC (AS3933) through GPIO pins and SPI serial interface. The control configurations are exchanged through SPI bus and received data is transferred from the receiver IC to micro-controller using GPIO pins.

Three coils in spherical configuration, along with their matched tuning capacitors, are connected to the transmitter or receiver via a multiplexer. All three coils independently receive the three signals, which are fed to the three input ports of the AS3933 simultaneously; which then forwards the signal with highest strength to the micro-controller.

Table II shows the current requirement of the sensor node in each of the state. The sensor node is battery powered and require power supply of 3.6 V. It can be seen that in Idle state the current consumption is ultra low which keeps the overall energy consumption of the sensor node extremely low.

Table III shows the components that are ON or OFF during a specific state. During Idle state the power consumption is minimum as receiver IC is the only component that is kept ON. The MCU is in deep sleep mode and the other components are kept OFF. During the Receive state, the receiver IC wakes up the micro-controller which then receives the data. During the

TABLE II
CURRENT CONSUMPTION IN EACH STATE

Idle	Receive	Data Acquire	Channel Sensing	Transmit (mW)
50 uA	200 uA	250 uA	200 uA	1.12 mA

TABLE III
ACTIVE AND IN-ACTIVE COMPONENTS IN EACH STATE

Working Mode	**Components**	**Power Mode**
Idle State	Micro-controller	Sleep
	Receiver Circuitry	ON
	Transmit Circuitry	OFF
	Sensors	OFF
Receive State	Micro-controller	ON
	Receiver Circuitry	ON
	Transmit Circuitry	OFF
	Sensors	OFF
Data Acquire State	Micro-controller	ON
	Receiver Circuitry	OFF
	Transmit Circuitry	OFF
	Sensors	ON
Channel Sensing State	Micro-controller	ON
	Receiver Circuitry	ON
	Transmit Circuitry	OFF
	Sensors	OFF
Transmit State	Micro-controller	ON
	Receiver Circuitry	OFF
	Transmit Circuitry	ON
	Sensors	OFF

Data Acquire state, the micro-controller turns ON the sensor power, acquires the data and then turns OFF the sensor power. During the Channel Sensing state the two active components are micro-controller and the receiver IC. The receiver IC sense the channel and the micro-controller keep track of the sensing time. During the Transmit state, the micro-controller turns OFF all other components and turns ON the transmitter power.

V. CONCLUSION

The paper presents an energy efficient MAC layer protocol for wireless sensor networks. The MI based sensor design has been presented and believed to bring an insight in the terrestrial and underwater research community. State diagram of the MAC protocol is described and power consumption in each state is given to get the idea of the power in each state.

REFERENCES

[1] A. Willig, "Wireless sensor networks: Concept, challenges and approaches," *Elektrotechnik und Informationstechnik*, vol. 123, no. 6, pp. 224–231, 2006.

[2] D. Makhija, P. Kumaraswamy, and R. Roy, "Challenges and Design of Mac Protocol for Underwater Acoustic Sensor Networks," *Electrical Communication*, pp. 0–5, 2006.

[3] M. Zhang and S. Wang, "An novel energy-efficient MAC protocol based on collision avoidance for wireless sensor networks," *Wireless Communications, Networking and Mobile Computing, 2009. WiCom'09. 5th International Conference*, no. 08, pp. 1–4, 2009. [Online]. Available: http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5303266

[4] W. Ye, J. Heidemann, and D. Estrin, "An energy-efficient MAC protocol for wireless sensor networks," *21st Conference of the IEEE Computer and Communications Societies*, vol. 3, pp. 1567–1576, 2002. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=1019408

[5] B. Alsaify and D. Thompson, "Pendulum: An energy efficient protocol for Wireless Sensor Networks," *Sensors Applications Symposium (SAS), 2010 IEEE*, pp. 7–11, 2010.

[6] S. C. Choi, J. W. Lee, Y. Kim, and H. Chong, "An energy-efficient MAC protocol with random listen-sleep schedule for wireless sensor networks," *IEEE Region 10 Annual International Conference, Proceedings/TENCON*, 2007.

[7] X. Fafoutis, "Medium Access Control in Energy Harvesting - Wireless Sensor Networks Xenofon Fafoutis," 2014.

[8] Y. He and X. Wang, "An Aloha-Based Improved Anti-Collision Algorithm for RFID Systems," no. August, pp. 86–95, 2013.

[9] Y. Gadallah and M. Jaafari, "A Reliable Energy-Efficient 802.15.4-Based MAC Protocol for Wireless Sensor Networks," *Wireless Communications and Networking Conference (WCNC), 2010 IEEE*, pp. 1–6, 2010.

[10] X. Han, L. Shu, Y. Chen, and H. Zhou, "WX-MAC: An Energy Efficient MAC Protocol for Wireless Sensor Networks," *2013 IEEE 10th International Conference on Mobile Ad-Hoc and Sensor Systems*, pp. 423–424, 2013. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=6680274

[11] Y. Kim, H. Shin, and H. Cha, "Y-MAC: An energy-efficient multi-channel MAC protocol for dense wireless sensor networks," *Proceedings - 2008 International Conference on Information Processing in Sensor Networks, IPSN 2008*, pp. 53–63, 2008.

[12] D. Lee and K. Chung, "RA-MAC: An energy efficient and low latency MAC protocol using RTS aggregation for wireless sensor networks," *2008 International Conference on Advanced Technologies for Communications*, pp. 150–153, 2008. [Online]. Available: http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=4760542

[13] N. Radio and S. Conference, "C21 . E2MAC : An Energy-Efficient MAC Protocol for Wireless Sensor Networks," pp. 244–251, 2014.

[14] S. Siddiqui and S. Ghani, "ES-MAC: Energy Efficient Sensor-MAC protocol for Wireless Sensor networks," *2013 10th IEEE INTERNATIONAL CONFERENCE ON NETWORKING, SENSING AND CONTROL (ICNSC)*, pp. 28–33, 2013. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=6548706

[15] L. Tang, Y. Sun, O. Gurewitz, and D. B. Johnson, "PW-MAC: An energy-efficient predictive-wakeup MAC protocol for wireless sensor networks," *Proceedings - IEEE INFOCOM*, pp. 1305–1313, 2011.

[16] P. Xie and J.-H. Cui, "R-MAC: An Energy-Efficient MAC Protocol for Underwater Sensor Networks," *International Conference on Wireless Algorithms, Systems and Applications (WASA 2007)*, no. 0644190, pp. 187–198, 2007. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=4288230

[17] Z. Azar and M. Manzuri, "A latency-tolerant MAC protocol for underwater acoustic sensor networks," *Control Automation and Systems (ICCAS), 2010 International Conference on*, pp. 849–854, 2010. [Online]. Available: http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5669755

[18] K. Chen, M. Ma, E. Cheng, F. Yuan, and W. Su, "A Survey on MAC Protocols for Underwater Wireless Sensor Networks," *IEEE Communications Surveys & Tutorials*, vol. 16, no. 3, pp. 1433–1447, 2014. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=6757189

[19] J. Cheon and H.-s. Cho, "A delay-tolerant OFDMA-based MAC Protocol for Underwater Acoustic Sensor Networks," pp. 1–4, 2011.

[20] C. C. Hsu, K. F. Lai, C. F. Chou, and K. C. J. Lin, "ST-MAC: Spatial-temporal MAC scheduling for underwater sensor networks," *Proceedings - IEEE INFOCOM*, pp. 1827–1835, 2009.

[21] W. H. Liao and C. C. Huang, "SF-MAC: A spatially fair MAC protocol for underwater acoustic sensor networks," *IEEE Sensors Journal*, vol. 12, no. 6, pp. 1686–1694, 2012. [Online]. Available: http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6086556

[22] "C-MAC: A TDMA-Based MAC Protocol for Underwater Acoustic Sensor Networks," *2009 International Conference on Networks Security, Wireless Communications and Trusted Computing*, vol. 1, pp. 728–731, 2009.

[23] M. K. Park and V. Rodoplu, "UWAN-MAC: An energy-efficient MAC protocol for underwater acoustic wireless sensor networks," *IEEE Journal of Oceanic Engineering*, vol. 32, no. 3, pp. 710–720, 2007.

[24] S. A. Samad, S. K. Shenoy, G. S. Kumar, and P. R. S. Pillai, "RMAC-M: Extending the R-MAC protocol for an energy efficient, delay tolerant underwater acoustic sensor network application with a mobile data mule node," *Proceedings of the 2011 International Symposium on Ocean Electronics, SYMPOL-2011*, pp. 217–223, 2011.

[25] N. Ahmed, J. Hoyt, A. Radchenko, D. Pommerenke, and Y. R. Zheng, "A multi-coil magneto-inductive transceiver for low-cost wireless sensor networks," in *Underwater Communications and Networking (UComms), 2014*, Sept 2014, pp. 1–5.