Comparative Performance Evaluation of MAC Layer Protocols for Underwater Wireless Sensor Networks

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Abstract

Underwater Acoustic Wireless Sensor Networks (UAWSN) use acoustic communication for transmitting data. High bit error rate, long propagation delay and limited bandwidth in underwater harsh environment are big issues for designing wireless sensor networks for many applications including ocean monitoring. Another consideration in UWASN is energy constraint. Similar to other wireless sensor networks the design process of energy and efficient bandwidth and also propagation-delay-aware MAC protocols are great challenges in UWASN. In this paper, the performance of three underwater MAC protocols for underwater environment, R-MAC, Slotted FAMA and UWAN-MAC are evaluated. Throughput, energy consumption and packet drop rate are those parameters which are considered for evaluating their performances. These protocols are implemented in Aqua-Sim, an NS-2 based simulator for underwater sensor networks. The simulation results show the effectiveness of the proposed method.

Keywords: Underwater acoustic sensor networks, MAC protocols, R-MAC, Slotted FAMA, UWAN_MAC

1. Introduction

Underwater sensor networks consist of a number of sensor nodes that communicate with each other using acoustic signal. Data are collected and forward to a sink node. Nowadays, UWASN are used for applications such as environmental monitoring, mine reconnaissance, disaster prevention, and distributed tactical surveillance (R. Manjula & S. Manvi, 2011). Since electromagnetic signal has high attenuation in water environment; it isn't suitable for underwater communication (J. A. Catipovic, 1990). Instead UWASN use acoustic signal for transmitting data. Acoustic signals have extremely limited bandwidth, travel slowly (1500 m/s) and have high bit error rate due to the noise, refraction and multipath interference (Zaihan Jiang, 2008). In UWASN, power management is very important because of limited battery power and also batteries cannot be recharged or changed when depleted (R. Manjula & S. Manvi, 2011). The MAC layer protocols operate directly on top of the physical layer. The main role of the MAC layer protocol is to decide when a node accesses a shared medium and to resolve any conflicts between nodes. The MAC layer protocols perform tasks such as flow control, framing and possibly correct errors that may occur in the physical layer.

Existing MAC layer protocols can be divided into two categories. Contention free or schedule based protocols and contention-based protocols. Contention based protocols allow nodes to access the shared medium at the same time and provide methods to reduce the number of collisions. Contention based protocols is suitable for distributed topologies. Carrier Sense Multiple Access (CSMA) is one of the contention based protocols that is used to reduce the collision between two or more stations (L. Kleinrock & F. A. Tobagi, 1975). If propagation delay compared to packet duration is small and network is fully connected, CSMA is efficient (M. Molins & M. Stojanovic, 2006). CSMA has hidden terminal and exposed terminal problems. In Figure 1, hidden terminal problem occurs when node A and node C cannot overhear each other's signals. Hence it is possible for C and A, to send data to B simultaneously and causing a collision at B. Exposed terminal problem occurs when C can send data to D, but it overhears an ongoing transmission from node B to node A and decide to wait.

To address these two problems, MAC protocols use RTS/CTS control packets. When a node wants to send data to another node, it send RTS (ready to send) packet to the receiver. When receiver receive RTS, it responds with CTS (clear to send) packet. Other nodes that overhear RTS or CTS, know that a data transfer will occur, and they wait.

In contention free protocols only one device can access the shared medium at any given time and is suitable for centralized topologies. Some of the contention free protocols are TDMA, FDMA and CDMA. FDMA isn't suitable for underwater environment, because available bandwidth is limited and FDMA divides bandwidth into several sub-bands and assigns one of them to a particular node (Zaihan Jiang, 2008). Also TDMA and CDMA aren't useful for acoustic networks because these protocols have some problems such as synchronization and near far problem (P. Xie & J. H. Cui, 2007). Underwater MAC layer protocols should also consider node mobility, low bandwidth, energy efficiency and long propagation delay. Due to the long propagation delay, node mobility and other underwater environment constraints, distributed topologies are used more than centralized topologies. Hence contention based protocols such as R-MAC, Slotted FAMA and UWAN-MAC are useful for such topologies. In this paper, we describe these protocols and compare their performance considering throughput and energy consumption parameters.

The rest of this paper is organized as follows. Section 2 describes the three MAC protocols that we considered in this paper. The performance evaluations of the above MAC protocols are investigated in section 3. Finally, section 4 concludes the paper.

2. Description of the Protocols

2.1 R-MAC

R-MAC is proposed by (P. Xie & J. Cui, 2007). The main goals of R-MAC are energy efficiency and fairness. R-MAC avoids data packet collision, schedules the transmissions of data packets and control packets. R-MAC also solve exposed terminal problem. It schedules the transmission of control packets and data packets at both the sender and the receiver instead of using the RTS/CTS packet. To reduce the energy consumption on idle state and overhearing, in R-MAC each node works in listen and sleep modes periodically. In R-MAC each node has three phases, namely, latency detection, period announcement and periodic operation.

In latency detection phase, each node powers on and randomly selects a time to broadcast a control packet, called ND (neighbor discovery). When a node receives NDs packet from its neighbors, it stores the arrival times of these packets, selects a time to send ACK-ND (acknowledge packet) randomly. ND and ACK-ND have the same size. After receiving the ACK-ND, the source node can compute the propagation latency.

In periodic announcement phase, each node randomly schedules and broadcasts its own start time of listen/sleep periodic operations for the third phase. It sends a packet which is called SYN. When a node receives broadcast packets (SYN) from its neighbors, converts the received schedules to its own schedule. In this phase, each node can records the schedules of its neighbors by exchanging SYN packets.

In periodic operation phase, each node wakes up and sleeps periodically. In this phase, nodes communicate by exchanging REV, ACK-REV, DATA, and ACK-DATA packets. If a node wants to send data, it sends a REV packet to reserve a time slot at the receiver. When receiver is ready for receiving data, it will notify all its neighbors by ACK-REVs about reserved time slot. All nodes that overhear ACK-REVs, stays silent in their corresponding time slots. Hence sender can send data packet at the reserved time slot. Data packets are transmitted in a burst. Each node can queue its data for the same receiver and sends all the queued data packets. To improve the channel utilization and reduce the control packet overhead, the receiver sends an ACK-DATA packet to the sender at the end of the burst transmission.

R-MAC is a fair MAC layer protocol. Because an intended receiver can provides equal opportunities for making reservation for all its neighbors using REV and ACK-REV packets. This protocol is good when no new node joins the network and all the nodes are static.

Advantage of R-MAC is that no synchronization and centralized scheduling are required. Disadvantage of R-MAC is that there is no technique proposed for the node which wants to change its transmission schedule, or when a node fails or a new node joins the network (F. Yunus, S. Ariffin & Y. Zahedi, 2010).

2.2 Slotted FAMA

Slotted FAMA proposed by (M. Molins & M. Stojanovic, 2006). This protocol is based on FAMA (C. L. Fullmer & J. Garcia-Luna-Aceves, 1995). FAMA use RTS/CTS message exchange for transmitting data. In FAMA to overcome MACA protocol problems, RTS length should be greater than maximum propagation delay and CTS length should be greater than twice maximum propagation delay plus RTS length. FAMA is not suitable for underwater environment; Because RTS and CTS length depend on propagation delay which is high in underwater environment (M. Molins & M. Stojanovic, 2006). If RTS/CTS are not used, collision can occur. Slotted FAMA were proposed to overcome this problem. In Slotted FAMA time is divided into slots and each packet has to be transmitted at the beginning of the slot. Slot length should be $\tau + \gamma$, where γ is the transmission time of CTS packet and τ is the maximum propagation delay. It is guaranteed that CTS or RTS packet transmitted at the beginning of a slot is received by all the neighbors.

In Slotted FAMA, when a node has a packet to send, it waits for the next slot and sends an RTS packet. The RTS packet is received by the receiver and all the nodes in the neighborhood of the sender. Neighbor nodes should wait two slots until receiver send a CTS and sender start sending data packets. At the beginning of the next slot, the receiver node sends a CTS packet. The CTS packet is received by the source node and all the nodes in the neighborhood of destination node. Neighbor nodes should wait until source node transmits entire data packets and receive ACK packets. When the source node received CTS packet, it waits until the beginning of the next slot time to transmit the data packet. Neighbor nodes should wait long enough until destination node transmit ACK or NACK packet. When the destination node receives the data packet successfully, it sends an ACK packet to the source node, otherwise it sends NACK. If neighbor nodes hear NACK, they should wait until complete data packets are transmitted and new ACK is sent. Figure 2 illustrates a successful handshaking.

To increase efficiency, Slotted FAMA use trains of packets technique. In this technique, each node has local queue. When a node establishes communication with a node, it will transmit all the packets that should be sent to that node in the queue. Therefore one handshaking is adequate for sending multiple packets.

In Slotted FAMA, use of ACK/NACK introduces exposed terminal problem. According to the Figure 1, if node B receives an ACK packet from node A, then node C should not send data and wait until transmission is completed. Therefore, use of ACK/NACK packet is only useful for a channel with high bit error rate and multiple hops.

Main advantage of Slotted FAMA is that it reduces collisions. It doesn't require the size of data packets either. Main disadvantage of Slotted FAMA is that it doesn't consider power control and energy consumption.

2.3 UWAN-MAC

UWAN-MAC proposed by (M. Kyoung Park & V. Rodoplu, 2007). The main goal of UWAN-MAC protocol is the energy efficiency. In sleep mode, energy consumption is less than idle listening mode. Therefore, UWAN-MAC tries to increase sleep mode interval in each node to reduce energy consumption.

In Figure 3, node A broadcasts its SYNC packet that contains its transmission cycle period "T_A" at the beginning of its cycle period and goes to sleep. Node B that is close to node A receives SYNC packet. Receiving SYNC packet allows node B to wake up at the correct time to listen to node A without any knowledge of the propagation delay. In this scheduling algorithm, there is no need for synchronization because nodes use relative time stamp.

In this protocol, initial transmission time selected randomly by each node. Figure 4 describes this protocol initialization phase. In initialization phase, each node broadcasts its SYNC message and receives its neighbor's SYNC packets, waits until the beginning of the next cycle. Each node inserts T_i to its SYNC packet to inform its neighbors that it will send data again after this time period. After network initialization, T_i is equal to T_o for all nodes to initialize their transmission and listen schedules.

Each node selects its transmission start time in interval (0, T_o) randomly and broadcasts and sends its SYNC packet to its neighbor. After initialization phase, every node has its listening and transmitting periods and wakes up in listening period for receiving its neighbor's packets or wakes up in the transmitting period for transmitting its own data. UWAN-MAC is suitable for networks with the stationary nodes. It is an energy efficient protocol

(M. Kyoung Park & V. Rodoplu, 2007). Since UWAN-MAC use only one control packet, it is bandwidth efficient. Main disadvantage of UWAN-MAC is that collision can occur when a node is transmitting.

3. Performance Evaluation

In this section, we compare performance of RMAC, Slotted FAMA and UWAN-MAC Protocols. We compare these protocols in Aqua-Sim, an NS-2 based simulator for underwater sensor networks (http://uwsn.engr.uconn.edu). We use the Table 1 parameters in the all simulation scenarios.

In our simulations, we consider the following two scenarios:

3.1 First Scenario

In this scenario, we consider throughput and energy consumption for the protocols. The topology is shown in Figure 5. In the simulation, number of nodes are 25, which 15 nodes are sender and 10 nodes are receiver. Positions of each node are chosen randomly. Traffic is generated according to a Poisson process. Each sender node sends 0.02 packets per second. Simulation time is 10000 seconds.

The results for throughput are shown in Figure 6. As shown in Figure 6, the throughput for Slotted FAMA is higher than RMAC and UWAN-MAC. Because Slotted FAMA doesn't choose transmission time randomly, but in RMAC and UWAN-MAC, senders do choose transmission times randomly. Moreover in RMAC, it is possible that when a node sends packets, the other nodes are in sleep mode. Figure 7 shows the result of energy consumption. As we can see, RMAC and UWAN-MAC energy consumption is lower than Slotted FAMA. This is mainly caused by two factors. First, Slotted FAMA doesn't consider energy conservation and doesn't have sleep mode. Second, in RMAC and UWAN-MAC protocols, each node can switch to sleep mode after sending or receiving its data. As shown in Figure 7, RMAC is much more energy efficient than the others.

3.2 Second Scenario

In this scenario, we consider throughput, energy consumption and packet drop rate parameters for the protocols. The topology is shown in Figure 8. In the simulation, number of nodes is 8. Numbers of sender nodes are 6 and 2 nodes are sink. The other nodes transmit data to the sink nodes. The distance between any two adjacent nodes is 100 meters. Simulation time is 3600 seconds and we repeat simulation 10 times.

The throughput is shown in Figure 9. We can see that the throughput of the three protocols increases linearly as the data generation rate increases. As we mentioned earlier, Slotted FAMA doesn't reserve channel for transmission and it sends packets in the beginning of its slot if the medium is idle. But in RMAC and UWAN-MAC, each node first reserve channel for its transmission. Therefore, as the traffic rate increases, the throughput for Slotted FAMA is much better than RMAC and UWAN-MAC. Moreover as we will further discuss, Slotted FAMA has also lower drop rate.

Figure 10 shows the result of energy consumption. From Figure 10, we observe that energy consumption is high in Slotted FAMA. This is mainly caused by three factors. First, Slotted FAMA receives more packets than UWAN-MAC and RMAC. Second, in UWAN-MAC and RMAC, nodes can go to sleep mode when they are not sending or receiving. But in Slotted FAMA, sleep mode is not considered. Third, Slotted FAMA uses RTS/CTS control packets which consume energy. RMAC and UWAN-MAC are more energy efficient than Slotted FAMA.

The results of drop rate are shown in Figure 11. From this figure we can see that the drop rate increases linearly as the data generation rate increases. As we mentioned earlier, main advantage of Slotted FAMA is that it reduces collisions between data packets. Because in Slotted FAMA, each node exchanges RTS/CTS control packets for sending or receiving and notifies its neighbor nodes. But in RMAC and UWAN-MAC, it is possible that two nodes have the same transmission period. We can conclude from Figures 9- 11 that UWAN-MAC and RMAC are energy efficient protocols. But their drop rate is high and receive rate is low.

4. Conclusions

In this paper, we present a comparative performance evaluation of three MAC protocols for underwater acoustic wireless sensor networks. We have considered two scenarios that are typical case of the current underwater channel access. We consider throughput, energy consumption and packet drop rates as our performance evaluation parameters. We showed that if we need to transmit more data and energy consumption isn't important, we can use Slotted FAMA. Also if reliable communication is needed, Slotted FAMA is better than RMAC and UWAN-MAC. But if energy is limited and data is large, we can use RMAC or UWANMAC. Simulation results show that RMAC is more reliable than UWAN-MAC. Both RMAC and UWAN-MAC are energy efficient and are useful for underwater environment because we can't recharge or change batteries. Since Slotted FAMA uses RTS/CTS control packets and these packets have large sizes with compare to other two protocols, it uses more bandwidth. In the future, we will consider more scenarios to compare these three Mac protocols.

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Table 1. Simlation Parameters

Topology area	500m*500m
Topology depth	500m
Transmission power	0.6 watt
Receive power	0.3 watt
Idle power	0.01 watt
Maximum transmission range	100 m
Routing protocol	VBF(vector based forwarding)
Bandwidth	10 Kbps
Frequency range	25 KHz

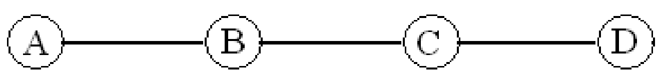

Figure 1. Hidden and expose terminal problems (M. Molins and M. Stojanovic. 2006)

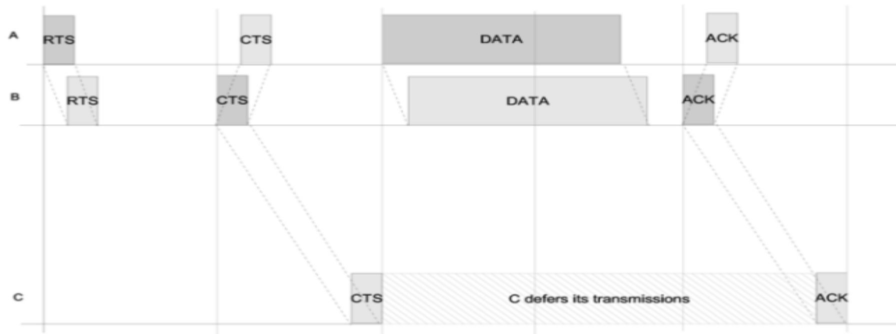

Figure 2. A successful handshaking in Slotted FAMA (M. Molins and M. Stojanovic. 2006)

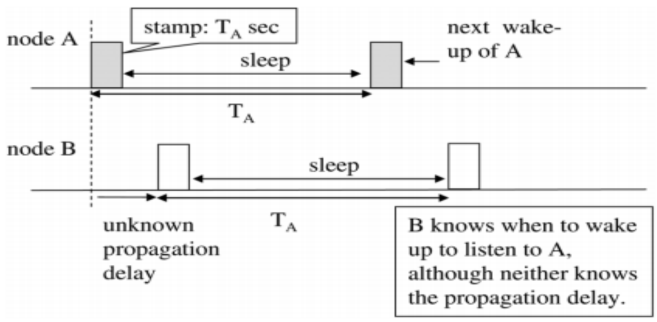

Figure 3. Listen cycle determination in UWAN-MAC (M. Kyoung Park and V. Rodoplu. 2007)

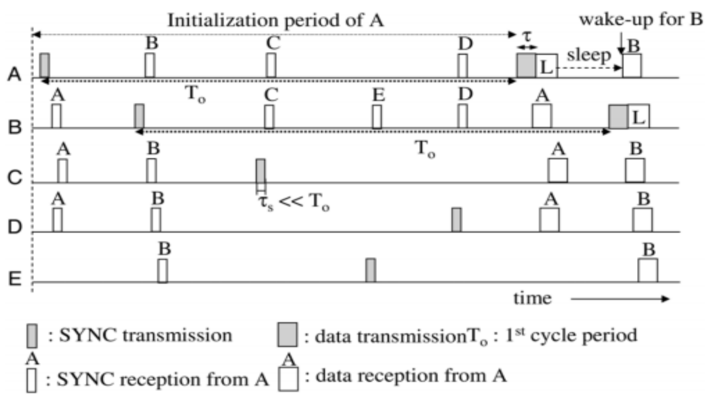

Figure 4. Initialization phase in UWAN-MAC (M. Kyoung Park and V. Rodoplu.2007)

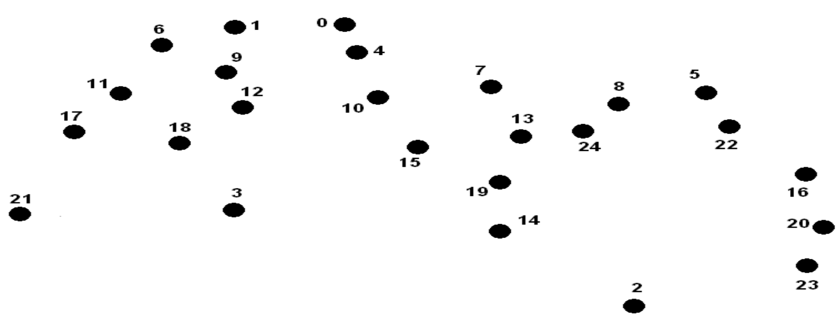

Figure 5. The topology used for first scenario

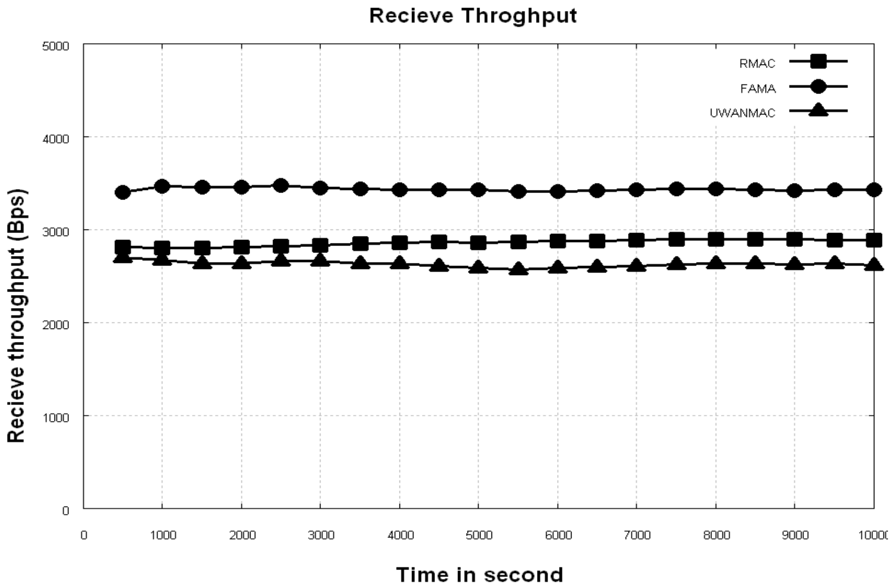

Figure 6. Throughput for first scenario

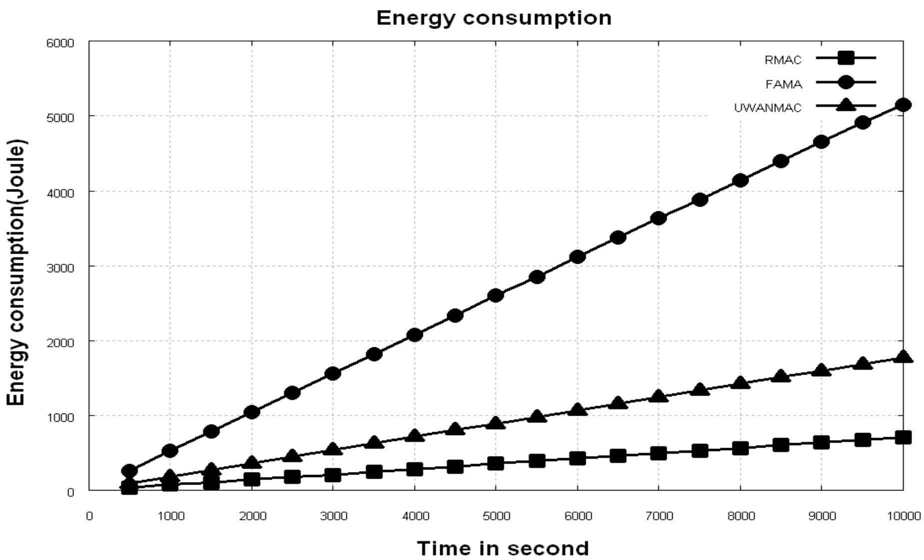

Figure 7. Energy consumption for first scenario

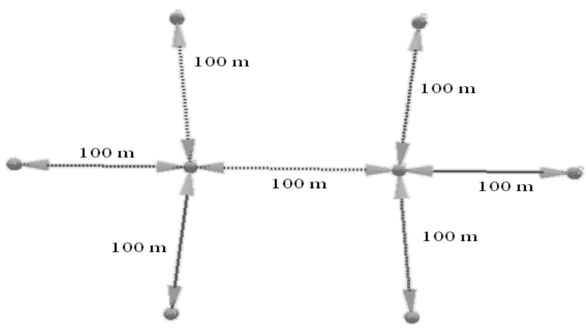

Figure 8. The topology used for second scenario

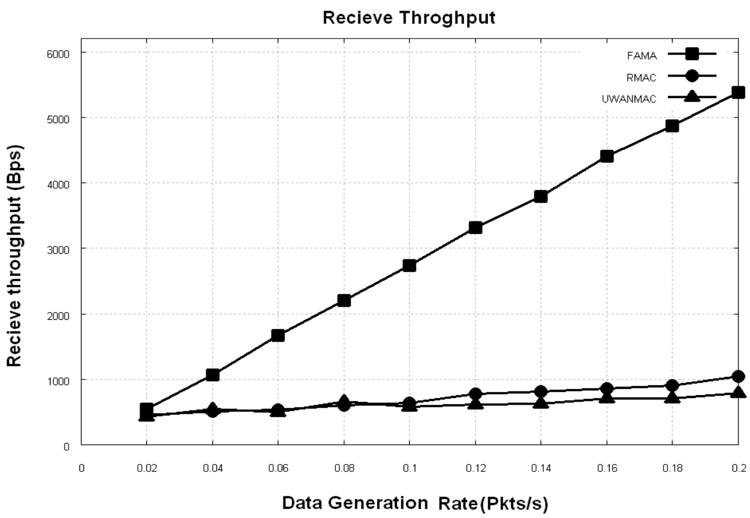

Figure 9. The throughput for second scenario

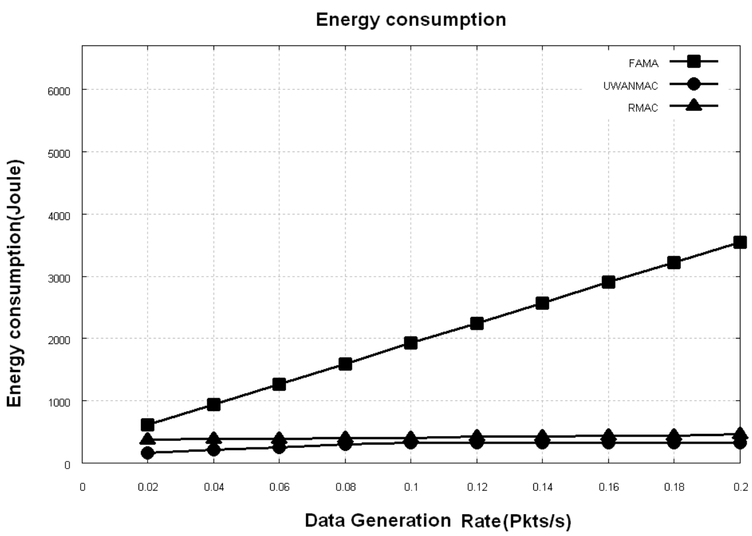

Figure 10. Energy Consumption for second scenario

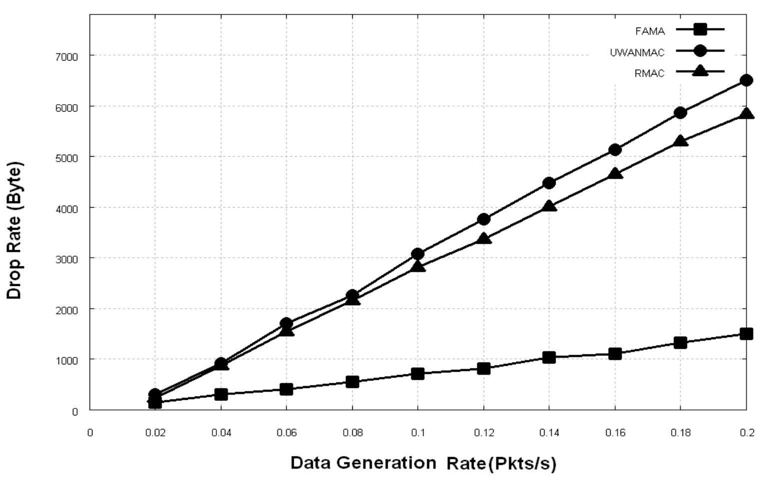

Figure 11. Drop rate for second scenario