CHAPTER 4
NOTEWORTHY CONTRIBUTION IN THE FIELD OF PROPOSED WORK

4.1 MAC Protocols for Wireless Sensor Networks

Various MAC protocols for wireless sensor networks have been discussed in this chapter. These protocols are classified into contention-based, contention-free and hybrid protocols.

4.1.1 Contention-based protocols

(a) S-MAC

S-MAC from Figure 4.1 consists of three major components: periodic listen and sleep, collision and overhearing avoidance, and message passing.

![S-MAC protocol design](image)

**Fig. 4.1 S-MAC protocol design**

*Periodic Listen and Sleep*

In many sensor network applications, if no sensing event occurs, then nodes remain idle for a long time. Compared to TDMA Protocols, S-MAC requires much lesser synchronization among neighbouring. The drawback of the scheme is that latency is increased due to periodic sleep of each node.
Collision and overhearing avoidance

S-MAC protocol follows RTS/CTS exchange. All senders perform carrier sense as shown in figure 4.2 before initiating packet transmission.

![Diagram of multi-hop network](image)

Fig. 4.2 Transmission on multi-hop network

As shown in Figure 4.2, nodes A, B, ... F forms a multi-hop network [61] and each node hears the transmissions from its neighbours. Suppose node B is currently transmitting a data packet to A. It is shown that C goes to sleep since its transmission interferes with A’s reaction. Node E and F do not need to go to sleep. D is two-hop away from A, and its transmission does not interfere with A’s reception, so it is free to transmit to its other neighbours like F. However, D is unable to get any reply from F, e.g., CTS or data because F’s transmission collides with B’s transmission at node D. So D’s transmission is simply waste of energy. That means all immediate neighbours go to sleep after they sensing RTS or CTS packet.

(b) T-MAC

T-MAC (Timeout MAC) [31] is a contention-based, energy efficient MAC protocol. T-MAC reduces energy intake by introducing an active/sleep duty cycle. TDMA-based protocols are naturally energy preserving, and do not suffer from collisions [85].

Every node in T-MAC periodically wakes up to communicate with its neighbours using a Request-To-Send (RTS), Clear-To-Send (CTS), Data, Acknowledgement (ACK) scheme that provides both collision avoidance and reliable transmission, and then goes to sleep again until the next frame as shown Figure 4.3. In the meantime new messages are queued. In the active period, a node will keep listening and potentially sending the messages. When no activation event has occurred then active period ends for a time TA.
Every node in T-MAC transmits its queued messages at the start of the frame. A node may expect to be in the medium every time it sends an RTS. The RTS transmission starts by waiting and listening for a random time within a fixed contention interval. T-MAC uses much less energy than S-MAC especially when the message frequency during the events increases. But T-MAC suffers from the early sleeping problem because of large number of edge nodes.

(c) R-MAC

Reservation-MAC (R-MAC) [86] is a contention based protocol, uses two separate periods. Initially, nodes compete for time slots reservation. This is mainly for their future transmissions. In the next period, each node transmits or receive data from the corresponding sender. A node is active only in these time slots, otherwise it goes to sleep. R-MAC is slightly better than S-MAC and T-MAC in energy consumption.

R-MAC protocol is used to solve overhearing avoidance by adjusting the listen-sleep durations depending on the traffic load of the network. It also reduces the collisions to save energy. Each node makes an advance reservation of the channel for its next
transmission to know which sender or receiver is involved during the time slot and accordingly the nodes can schedule their sleep and wake up periods to avoid overhearing. R-MAC uses variable duration of the listen and sleep periods according to the traffic load. The listen period can be extended or reduced when traffic is increased or decreased to minimize the collisions.

(d) TA-MAC

TA-MAC protocol is based on S-MAC protocol uses both active and sleep periods. The duty cycle mechanism proposed in the S-MAC protocol is energy efficient. The packet forward latency is increased, but throughput in the network is decreased. TA-MAC protocol [32] solves this problem by using Busy-Signal (BS) packet. In case every node chooses the node closest to the sink from its neighbours as its next hop, such as node B in Figure 4.4, overhears a CTS packet destined for another node. It sends a BS packet to its next-hop receiver (node A) immediately, no matter whether it has packets to send or not. In the active period, all nodes perform virtual and physical carrier sense before the time of transmission. The main function of TA-MAC is that a node goes to sleep if it fails to get the medium.

Fig. 4.4 Busy-Signal packet forward delay problem
Suppose, when the previous-hop node, such as E in Figure 4.4, overhears an RTS sent by its next-hop node (node D), it should wait for SP (short period between RTS and CTS) plus a CTS transmission time, and then try BS packet to its previous-hop sender (node F). The above transmission of BS can only start when carrier sense is successful.

It should be noted that the BS packet can help to improve the packet forward latency significantly because nodes downstream are ready for data and nodes upstream prohibited from sending are able to wake up in time to transmit, which also increases throughput.

(e) WiseMAC

Wireless Sensor MAC (WiseMAC) was proposed by Hoiydi et al. [87] handles both multi hop infrastructure networks. It combines non-persistent CSMA with synchronized preamble to improve energy efficiency. In the preamble sampling method, all nodes in a network sample the medium with the same constant period; on the other hand their relative sampling schedule offsets are independent. If a node finds the medium busy, it will continue to listen until it receives a data packet otherwise the medium becomes idle all over again. To minimize the power consumption experienced by the fixed-length preamble, WiseMAC presents an effective system to reduce the length of the wake up preamble.

4.1.2 Contention-Free Protocols

(a) TRAMA

Traffic adaptive medium access protocol (TRAMA) reduces power consumption by using unicast, multicast and broadcast transmissions [36]. TRAMA uses distributed election scheme in slotted time and determines which node can transmit at particular time slot. TRAMA is fair and avoids collision. The nodes which are not selected are going to sleep to provide adequate performance and energy efficiency. TRAMA is schedule-based, uses dynamic method to switch nodes to low power mode.

TRAMA consists of three components, namely, neighbour protocol (NP) which gathers information from neighbour nodes, Schedule Exchange Protocol (SEP) used to exchange
two-hop neighbour information and programs and lastly, adaptive election algorithm (AEA), which decides on the nodes for current time zone.

![Fig. 4.5 Time-slot structure of TRAMA](image)

There are two types of time slots namely random access slots for signaling and schedule access time slots for transmission as shown in Figure 4.5. Each node transmits by selecting a slot randomly depends on the type of network in random access mode. All nodes must be either transmit to neighbours or receive from the neighbours. Nodes addition and deletion is possible in random access periods only.

The major problems in random access time scheduling are loss of signaling packets due to collisions and implementation of protocol is complex. Nodes are either transmitting or receiving state in random access period leads to energy consumption. In scheduled access phase a node can announce the schedule to its neighbouring nodes according to MAC layer queue. Normally, the highest priority node is selected for next transmission. A node gives up the corresponding slot if it does not have enough packets to transmit and in the meanwhile other nodes can also utilize these slots.

(b) DE-MAC

Distributed Energy-Aware-MAC (DE-MAC) is a TDMA based MAC protocol [88] to address the energy management problem in WSNs. Idle listening and overhearing problem can be avoided by introducing periodic sleeping mechanism. A group of
neighbour nodes periodically perform local election process to elect the worst node as the winner and let the winner sleep more than the neighbour nodes.

A node can independently decide to initiate an election algorithm if its current energy level is below the threshold value. In the beginning of election process, each node sends its energy level to all of its neighbours. To receive the energy level information from other nodes, all nodes listen to all transmitted packets. A lowest energy node is elected at the end of the election process. One or more winners are elected by this process and winners have time slot twice the number of losers.

4.1.3 Hybrid protocols

(a) Z-MAC

Zebra-MAC (Z-MAC) is a combination of both CSMA and TDMA hybrid protocol [36]. It is robust to synchronization errors, but its performance always falls back to that of CSMA. A node can transmit in any time slot in Z-MAC that always performs carrier sensing and transmits a packet when channel is free. Collision is also reduced when senders (owners) have data to transmit. When a slot is not used by the owners then other nodes can use the slot.

<table>
<thead>
<tr>
<th>Table 4.1 Z-MAC time slot allocation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slot 0</td>
</tr>
<tr>
<td>Node 0</td>
</tr>
<tr>
<td>Node 1</td>
</tr>
<tr>
<td>Node 2</td>
</tr>
<tr>
<td>Node 3</td>
</tr>
</tbody>
</table>
Z-MAC introduces four parts namely neighbour discovery, slot assignment, local frame exchange and global time synchronization. The slot assignment is assigned at least one slot for transmission as shown in Table 4.1. A node can contend other’s transmission also if the owner of that slot has no data to send.

Z-MAC is good to handle synchronization error, but the problem in Z-MAC is that it does not solve hidden terminal problem, and also suffers huge overhead. Therefore, Z-MAC is not suitable for distinct nodes.

(b) Funneling-MAC

Funneling-MAC is the combination of hybrid TDMA and CSMA/CA MAC protocol [59]. It has a unique funneling effect [89], in this the events generated by the sensor fields travel hop-by-hop in many-to-one traffic pattern towards different sinks. Hence, by using TDMA in a localized manner and creating more management on the sink, the scalable problem can be solved and this will increase throughput and energy efficiency. The experimental results [89] shown that Funneling-MAC outperforms Z-MAC.

4.2 Analysis of MAC protocols

The main characteristics of energy efficient MAC protocols have been discussed in this thesis. The MAC protocol models are validated and compared in the detailed simulations. Each simulation results is the result of more than 15 runs with the outcome of the factors like collisions, latency, and the like.

4.2.1 Energy consumption

As sensors rely on batteries and also it will be difficult to change or recharge batteries in the sensors. A classical energy model was proposed by Heinzelman et.al [57], consists of low power consumption radio, and is shown Table 4.2.
Table 4.2 Radio model

<table>
<thead>
<tr>
<th>Radio Mode</th>
<th>Energy Consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmitter Electronics ($E_{Tx-elec}$)</td>
<td>50nJ/bit</td>
</tr>
<tr>
<td>Receiver Electronics ($E_{Rx-elec}$)</td>
<td></td>
</tr>
<tr>
<td>$E_{elec} = E_{Tx-elec} = E_{Rx-elec}$</td>
<td></td>
</tr>
<tr>
<td>Transmitter Amplifier ($E_{amp}$)</td>
<td>100 pJ/bit/m²</td>
</tr>
<tr>
<td>Idle ($E_{idle}$)</td>
<td>40nJ/bit</td>
</tr>
<tr>
<td>Sleep</td>
<td>0</td>
</tr>
<tr>
<td>Freespace model ($\varepsilon_{fs}$)</td>
<td>10pJ/bit/m²</td>
</tr>
<tr>
<td>Multipath model ($\varepsilon_{mp}$)</td>
<td>.0013pJ/bit/m²</td>
</tr>
<tr>
<td>Data length</td>
<td>2000 bits</td>
</tr>
<tr>
<td>Threshold distance ($d_0$)</td>
<td>$\sqrt{\varepsilon_{fs} / \varepsilon_{mp}}$ m</td>
</tr>
</tbody>
</table>

Energy used in transmitting or receiving one bit is found by using power value, i.e.

Energy = power * time ................................................................. (4.1)

The energy consumption of Mica2 is the sum of energy utilized for transmitting, receiving, listening, sampling and sleeping [33]. The calculation of energy in transmitting and receiving one bit is given as:

Energy = Current * Voltage * Time....................................................... (4.2)

It is possible to estimate sensor network lifetime for different protocols according to different states are known. Suppose, several nodes running simultaneously then calculations would be different due to the flooding effect inherent to the protocol. It is possible to find an upper limit for the energy consumption of the motes, according to Ch. Lu [90], in his experimental test bed; a node sends a packet every 80ms and every packet will take 9ms for sending and receiving. As soon as a node receives a packet it will retransmit it immediately. Let B be the bakeoff time, time to switch to radio mode is STx, time to transmit a frame is Tx and Srx be the time to switch to receive mode. Then, time frame is calculated as:
TF = B + STx + Ttxt + Srx. ................................................................. (4.3)

If Rtxt is the time taken to receive a frame, then the time cycle can be calculated as,

\[ T = B + 2STx + Rtxt + Ttxt. \] ................................................................. (4.4)

Typical sources of energy loss in wireless sensor networks include idle listening, packet collisions, protocol overhead, and message overhearing.

(a) Idle Listening

Idle listening occurs when a station listening an inactive medium. For example, Chipcon CC2420 transceiver of 250 kbps [91] node can transmit 4.1ms energy. Suppose a node can transmit and receive one 10ms message every second, then listening an idle channel for the remaining 980ms that means idle time is 98%. As many wireless sensor radios consume more energy in idle listening than normal transmissions, many energy efficient MAC protocols have been developed to reduce energy in the idle listening [48]. There are four techniques to reduce idle listening. They are: static sleep scheduling, dynamic sleep scheduling, preamble scheduling and off-line scheduling.

(b) Static Sleep Scheduling

S-MAC protocol [30] is designed to maximize the network lifetime as shown in Figure 4.1. Every frame in this protocol is divided in to listen and sleep period respectively. Listen period is further divided into synchronization period and data transfer period. The nodes periodically announce their sleep schedules thereby increasing 1% network lifetime. In sleep period a node listens for a SYNC message from its neighbour. That means the sender intends to sleep in \( t \) seconds. When a node hears its other nodes schedules, it adopts the same schedule and retransmits the schedule for other nodes to adopt. Within the time period, if a node does not hear any SYNC message, then the node will set and broadcast its own sleep schedule.
(c) Dynamic sleep schedule

T-MAC [31] protocol introduces a listening timeout mechanism by dynamically adapting an active listen period in response to network traffic to improve idle listening overhead. T-MAC adapts a timeout TA mechanism, the longest period in which the hidden node would have to wait before hearing the first bit of CTS message. The Figure 4.3 shows that T-MAC effectively divides the number of messages into smaller time frame thereby reduce idle time. Suppose a node is waiting for a timeout period without sensing any traffic, the node goes to sleep until the next scheduling time. T-MAC achieves five times the energy savings than S-MAC.

(d) Preamble scheduling

B-MAC (Berkeley-MAC) [33] and WiseMAC [87] organize sleep schedules by allowing nodes to adopt sleep schedule with fixed sleeping cycle frequency. Both the approaches use low power listening (LPL) method. As shown in Figure 4.6, if a node senses activity, it wakes up, synchronizes and receives the packet. In B-MAC authors have used MICA Mote for their experiments in which a sender must transmit a preamble length greater than each node’s sampling cycle to ensure that the node is awake for synchronization. This strategy is used to reduce idle listening, but works well in networks with scarce traffic.

![Fig. 4.6 B-MAC low power listening](image-url)
WiseMAC is the improvement of B-MAC in which instead of sending a long preamble, it can send a standard one during receiver’s sensing time period. The control packet overhead is reduced by keeping every node’s sleeping schedule in all other packet’s header. The main problem is that the multicast messages must span the entire frame.

(e) Offline scheduling

Traffic-Adaptive MAC (TRAMA) is a schedule-based protocol [34] that optimizes power savings during inactive periods by introducing Scheduling Exchange Protocol (SEP) to schedule message recipients and Neighbour Protocol [NP] to release unused time slots for reuse. TRAMA uses an Adaptive Election Algorithm (AEA) to randomly assign time slots. TRAMA establishes collision-free data transfer to maximize sleep time for effective utilization of channel utilization and also to minimize latencies. Generally schedule based protocols tend to waste time slots when no traffic. TRAMA overcomes this problem by adaptively scheduling nodes based on transmission requirements.

TRAMA frame is divided into contention and contention-free time periods as given in Figure 4.7. The contention period is used to exchange control messages to synchronize time and establish data transmission requirements. Nodes with no activity may sleep during this time period. TRAMA decomposes into three vital components namely Neighbourhood Protocols (NP), Schedule Exchange Protocol (WEP) and Adaptive Election Algorithm (AEA).

![Fig. 4.7 TRAMA frame structure](image)
The NP of TRAMA creates the 2-hop neighbourhood for every node for local synchronization. It helps to give the number of nodes added to and deleted from the sending node’s neighbour database. TRAMA will establish a high [92] probability (99%) of successful transmission. Sensor network radios transmit extremely limited data rates on the order of 250 kbps [91]; therefore, frame sizes may be on the order of 25ms.

The SEP is used to fix time slot for each individual packet. SEP saves energy by allowing nodes with no data to send or receive to sleep during the contention-free period. It is also used to increase data throughput by reallocating empty time slots for reuse. Figures 4.8(a) & (b) show the format for a data and signaling message.

<table>
<thead>
<tr>
<th>Source Addr</th>
<th>Timeout</th>
<th>Width</th>
<th>Number Slots</th>
<th>Bitmap 1</th>
<th>Bitmap 2</th>
<th>…</th>
<th>Bitmap n</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 4.8 (a) Signaling message

<table>
<thead>
<tr>
<th>Type</th>
<th>Source Addr</th>
<th>Dest Addr</th>
<th>Timeout</th>
<th>No. of slots</th>
<th>Rcvrs Bitmap</th>
<th>Data …</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 4.8(b) Data message

The AEA schedules the transmitters for a given time slot rendering to the neighbourhood. The time slot of the node’s priority can be calculated for each of its contending 2-hop neighbouring nodes for every time slot. With the time slot t and the node’s identification number k, AES uses the hash function for priority.

Priority(k,t) = hash(k concat t)

The highest priority node is ready to transmit data in that time slot or give it up for reuse, otherwise the next highest priority node that announce a scheduled requirement will take over. But the main drawback of TRAMA is that the protocol uses more control packets, which implies that it faces more overhead.

4.2.2 Frame collisions

When a wireless sensor node sends a MAC protocol frame, or a message, which collides with another message frame, collision occurs. The radio cannot simultaneously receive
while in transmit mode. Propagation delays between distant stations; and hidden nodes which are out of range of the sender, are the leading causes for wireless frame collisions.

S-MAC and T-MAC protocols use contention and RTS-CTS exchanges methods to reduce collisions. B-MAC protocol significantly reduces the frame collisions after the initial RTS has seized the channel.

4.2.3 Protocol overhead

In WSNs the protocol overhead consumes both energy and bandwidth and the networks serve as an integrated system to transfer data between the various distributed application layer programs. Adding data message headers and 2-to-1 Manchester encoding to the RFM TR1001 [93] transceiver reduces an effective 65% reduction [94].

4.2.4 Message overhearing

Receiving and discarding messages projected for other nodes is called message overhearing. Receiving all messages is an efficient method which will increase throughput and decrease latency specifically in cases where the radio receive mode spends more energy than the transmission mode. Early rejection allows a sensor node to turn off its radio once it has read the destination field for an incoming unicast message or for a broadcast message [93]. Message passing technique permits nodes to schedule a sleep period during an overheard RTS-CTS handshake sequence and this technique is implemented in S-MAC and T-MAC.

Table 4.3 Current consumption in receiving and sleeping mode

<table>
<thead>
<tr>
<th>Radio</th>
<th>Receive Mode</th>
<th>Power-down mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC2420 [93]</td>
<td>19.7A</td>
<td>1A</td>
</tr>
<tr>
<td>CC1000 [93]</td>
<td>9.6A</td>
<td>0.2A</td>
</tr>
</tbody>
</table>
4.2.5 Node energy capacity

IEEE 802.15.4 WSN transceiver platforms operate on two AA batteries and can achieve approximately 3000mAh with a 2.1 volt cutoff and a 20mA slow drain application [95]. The energy consumption rates for the devices in receive, transmit, and sleep modes can be measured experimentally. The current consumption in CC2420 and CC1000 is tabulated in Table 4.3.

(a) Energy consumption vs. Data load

The data load defines as the ratio of the number of nodes in the network and the sampling rate. In this experiment, the network size is kept static and the rate at which messages are injected into the network is different.

(b) Energy consumption vs. Latency

The tradeoff between energy consumption and latency is an important factor mainly for event-based applications such as burglar alarms. Usually every node sends a status message into an idle network and status message to its parent node in every 10 minutes this is done to check the availability. Normally the message latency depends on the protocol design. The average latency is calculated in real-time applications, but this may not change the picture for selecting the most suitable protocol. The latency and energy consumption of the models is compared with simulation namely S-MAC, B-MAC and L-MAC [30][33][96]. OMNeT++ is used to determine which packets are dropped due to contention interface.

4.3 Synchronization Procedure

4.3.1 Time synchronization

The applications of wireless sensor networks like building and industrial automation, military and scientific applications need low cost and low power wireless sensors which regularly take measurements, process and transmit them. In many cases these measurements must be taken as time-stamped and arranged in time. Based on the
application the time factor is depending on time-related computations [97], coordinated actions and data logging. The power consumption of WSN nodes is shown in Figure 4.9.

**Function generator**
Agilent 33220A

**Split cable**

**WSN nodes**

![Diagram of WSN nodes](image)

**Fig. 4.9 Power consumption of WSN nodes**

Time-related computations: In this method different sensor nodes measure one or more physical quantities [98] with the help of clocks. This time synchronization enables accurate and consistent results from different network nodes.

Coordinated actions: Generally, in wireless sensor networks the nodes are activated only at the time of communication and when the communication is finished the nodes have to switch off their radios to save energy. But without time synchronization the nodes fail to activate their radios at the same time. So coordinated actions and time synchronization is required to minimize data lose. Figure 4.10 shows the mechanism of radio packet at MAC and physical layer.

Data logging: Wireless sensor nodes continuously measure ambient variants [99]. Data logging also happens in hospitals or home [100]. The time referenced data are used in patient’s records in hospitals. Network nodes can periodically setting their timers.
4.3.2 Basic synchronization procedure

In WSN synchronization, transfer of time value from one node to another is the main procedure. The method is very simple, read the clock, put the time value in radio packet and finally send it. Node A reads the time value $T_a$ and node B can read the time value $T_b$. The difference in time $D$ can be computed as,

$$D = T_b - T_a \quad \text{(4.5)}$$

**Round-trip synchronization:**

In this procedure, node A sends a packet with timestamp $T_1$ to node B. After the communication delay $F$, node B receives the packet and records its time $T_2$.

$$T_2 = T_1 + F + D \quad \text{(4.6)}$$

Now node B sends a response packet with timestamp $T_3$ to node A. when the second packet arrives, node A makes timestamp $T_4$. Let us assume that the communication latency is symmetric and the value of $T_4$ is computed as,

$$T_4 = T_3 + F - D \quad \text{(4.7)}$$

Equation (3) – (2) gives the clock offset $D$

$$T_4 - T_2 = T_3 + F - D - T_1 - F - D \quad \text{(4.8)}$$

$$D = (T_3 - T_1 - T_4 + T_2) / 2 \quad \text{(4.9)}$$

Sum of the equations (2) & (3) can be used to compute communication delay $F$

$$T_2 + T_4 = T_3 + F - D + T_1 + F + D \quad \text{(4.10)}$$

$$F = (T_4 + T_2 - T_3 - T_1) / 2 \quad \text{(4.11)}$$

If the value of $D$ is known, node A can estimate the time of node B.

4.3.3 MAC layer time-stamping

Time-stamping method in MAC layer [101][102] is used to reduce the uncertainty in communications. In this method, a sending node records the time of the events that happen at the beginning of the packet transmission. It would then append that time value
to the packet, while the latter is being transmitted as shown in Fig. 4.10. The event is usually a signal, generated by radio model as in CC2420 radio [103]. The MAC layer then records this timer value by some special interrupt handling techniques.

**Fig. 4.10 Time-stamping function of radio packet at MAC and physical layer**

**Time-stamping at physical layer:** Time-stamps can be done in physical layer without modifying the protocol stack [104]. In this method, the radio must have an on-chip timer. Its value can be captured by radio like MC13192 [105] as shown in Figure 4.11. Generally physical layer timestamp is very accurate.

**Uncertainty of time transfer:** In the normal procedure, the receiver will receive the time value of the sender after some delay. This is due the amount of operations occurring between the moment when the sender’s timer is read and the receiver’s timer is updated [106]. There are six time periods available, which are given below.
Fig. 4.11 Measuring clock drifts of WSN nodes by a function generator Agilent 33220A

- Send time: the time spent by a transmitter for creating a packet at the application layer and sending the packet to the MAC layer.
- Access time: this is the time to access the wireless channel; this is depending on the network traffic and other functions of communication protocol.
- Transmission time: the time taken for an equivalent bit of information into modulated electromagnetic waves.
- Propagation time: The time consumed by one bit to cross the wireless channel from the source to the receiver.
- Reception time: The time required to convert a received electromagnetic wave into one equivalent bit of information.
- Receive time: It is the sum of the time to transfer the packet from MAC layer to the application layer.
4.3.4 Texas products

There are different Texas products [103] available in the market for analyzing WSNs, which include CC 2420, CC2430, CC1000, CC2431 and 2531. They differ in their properties of communication range, cost and operations.

CC 2420 is the IEEE 802.15.4 standard, used in ZigBee products. It has very low current consumption compared to other products [107] and is able to receive very low signal. It is used in wireless sensor networks, ZigBee and IEEE 802.15.4 systems. It is also used in home and building automation.