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IDMMAC: Interference Aware Distributed Multi-Channel MAC Protocol for WSAN

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Abstract

In this paper, an interference aware distributed multi-channel MAC (IDMMAC) protocol is proposed for wireless sensor and actor networks (WSANs). The WSAN consists of a huge number of sensors and ample amount of actors. Hence, in the IDMMAC protocol a lightweight channel selection mechanism is proposed to enhance the sensor's lifetime. The IDMMAC protocol divides the beacon interval into two phases (i.e., the ad-hoc traffic indication message (ATIM) window phase and data transmission phase). When a sensor wants to transmit event information to the actor, it negotiates the maximum packet reception ratio (PRR) and the capacity channel in the ATIM window with its 1-hop sensors. The channel negotiation takes place via a control channel. To improve the packet delivery ratio of the IDMMAC protocol, each actor selects a backup cluster head (BCH) from its cluster members. The BCH is elected based on its residual energy and node degree. The BCH selection phase takes place whenever an actor wants to perform actions in the event area or it leaves the cluster to help a neighbor actor. Furthermore, an interference and throughput aware multi-channel MAC protocol is also proposed for actor-actor coordination. An actor selects a minimum interference and maximum throughput channel among the available channels to communicate with the destination actor. The performance of the proposed IDMMAC protocol is analyzed using standard network parameters, such as packet delivery ratio, end-to-end delay, and energy dissipation, in the network. The obtained simulation results indicate that the IDMMAC protocol performs well compared to the existing MAC protocols.

Keywords

Actor, BCH, IDMMAC, Interference, Multichannel, PRR

1. Introduction

Wireless sensor and actor network (WSAN) is a collection of an ample amount of resource conservative sensors and a lower number of resource-rich actors. Each active sensor traces events in the network area and transfers it to the nearest actor, where an actor processes the data and executes efficient actions in the event area [1]. The sensors are static and energy constraint devices, but actors are resource-rich and have mobility. Hence, WSAN should take into account the requirements of both wireless sensor networks (WSNs) and ad-hoc networks. WSAN plays a crucial role in various real-time applications, such as fire-hazard monitoring, health, industrial, and home applications. These applications

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require a high throughput and fewer packet delay MAC protocols. IEEE 802.15.4 provides 16 non-orthogonal channels [2], but the existing MAC protocols do not utilize these channels to achieve better QoS parameters. So, in this paper, an interference aware distributed multi-channel MAC (IDMMAC) protocol has been designed to improve network performance. Existing single-channel MAC protocols do not perform well in a multi-channel environment, because they may create a multichannel hidden terminal problem in WSAN [3,4]. Fig. 1 depicts the multi-channel hidden terminal problem and it occurs due to the fact that nodes may listen to different channels. It makes it difficult to use a virtual carrier sensing mechanism to avoid the hidden terminal problem.

In Fig. 1, if node *X* wants to communicate with *Y*, then *X* sends an RTS packet using the control channel 1. *Y* chooses channel 2 for transferring the data, and sends a CTS packet to *X*. These control messages reserve channel 2 in the transmission ranges of *X* and *Y*. However, when node *Y* sends a CTS packet to *X*, node *Z* is busy receiving in another channel, so it does not hear the CTS packet. Hence, it does not know about any sort of communication taking place between *X* and *Y* on channel 2. If *Z* initiates the communication with *W* and selects channel 2, then, a collision will occur at node *Y*. This problem occurs when a node has a single transceiver and can listen to only one channel at any given instant time. To overcome this drawback, various researchers have proposed multichannel MAC protocols [5-7]. These protocols use a common channel to negotiate for the data channel. However, a default control channel decreases the network throughput. To eliminate this problem, in the IDMMAC protocol, each actor has *K* transceivers so that it can sense *K* non-interference channels simultaneously. The actors are resource rich nodes. Hence, embedding multiple transceivers is a feasible solution.

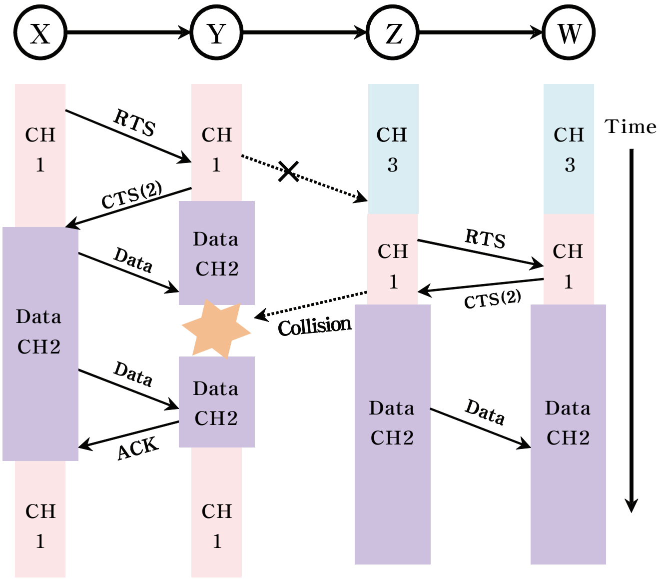


Fig. 1. Multi-channel hidden terminal problem.

The layout of the paper is organized as follows: Section 2 analyzes the existing MAC protocols for sensor networks. Section 3 describes the interference aware distributed multi-channel MAC protocol for sensor and actor networks. Section 4 gives a note on the analysis of results based on the used simulation parameters. Section 5 concludes the paper.

2. Related Work

Maximizing the lifetime of a network is a common objective in sensor networks. This is due to the fact that sensor are resource conservative nodes because battery replacement is not feasible. But in WSAN, both packet delay and network lifetime should be considered when designing a MAC protocol. The packet delay impacts the performance of the WSAN applications. On the other hand, due to the existence of a large number of resource conservative sensor nodes, it is important to consider network lifetime [8-12].

The existing MAC protocols can be classified into single channel and multi-channel MAC protocols, based on the number of channels available for each node. The single channel MAC protocols suffer from high collisions, network congestion, and hidden terminal problems. These problems degrade network performance. In a multichannel MAC protocol, the overall bandwidth is equally divided into *n* channels. Furthermore, the multichannel MAC protocols are classified into single transceiver and multi-transceiver multichannel MAC protocols. In the former, each node can transmit or listen on a single channel at any given time. These MAC protocols may also face the multichannel hidden terminal problem. Carley et al. [13] proposed a single channel MAC protocol for WSAN (PMSMAC). It uses a packet scheduler to provide priority for every node in accessing the channel So and Vaidya. [14] proposed a multi-channel MAC (MMAC) protocol for ad-hoc networks. The time duration is segregated into slots and each slot is further divided into an ad-hoc traffic indication message (ATIM) window and data transmission phase. In the ATIM window, every node transfers their channel negotiation messages in the default channel. In the data transmission phase, the sender transfers its data to the destination using the assigned channel. Chen et al. [15] proposed a MAC protocol for ad-hoc networks. It is also similar to a MMAC protocol, but the time slot duration is variable.

Jain et al. [16] proposed a MAC protocol for wireless networks, which is similar to a MMAC protocol. Each node maintains a table that consists of channel availability, channel busy time, and a preferable channel for the node. The node preferable channel list decreases the probability of collisions and increases the network throughput. Wu et al. [17] designed a dynamic channel assignment (DCA) mechanism for MANET. Each node consists of two transceivers that are dedicated for control and data channels. Saifullah et al. [18] analyzed the receiver and link channel allocation mechanisms. Finally, they concluded that a link-based channel allocation mechanism performs well in sensor networks and also proposed a distributed Min-Max channel allocation mechanism (DCAMAC) for WSN. The multiple transceiver protocols consume a lot of energy. Hence, these solutions do not suit for energy-constrained sensor networks.

To overcome these drawbacks, various authors have proposed multi-radio model solutions. In the multi-radio model, each node consists of two radios to transmit/receive data independently. So, it improves network QoS parameters at the cost of energy consumption. Bahl et al. [19] analyzed the impact of a multi-radio model in network performance. Wang et al. [20] proposed an energy-efficient protocol for a wireless LAN. Ramachandran et al. [21] proposed an interference-aware channel assignment for multi-radio wireless mesh networks. These MAC protocols improve network performance compared to single radio mechanisms, but they consume a lot of energy from the nodes. To the best of our knowledge there is still no proper multi-radio multichannel MAC protocol for WSAN.

3. Interference-Aware Distributed Multichannel MAC Protocol

In the IDMMAC protocol, each sensor selects a high capacity and packet reliability ratio (PRR) channel from its available channels to communicate with its cluster head (actor). It is a lightweight channel selection mechanism. Then, the actor selects a minimum interference and maximum throughput channel to communicate with its neighbor actor. This protocol achieves maximum throughput as it coordinates parallel transmissions over multiple non-interference channels.

3.1 Network Assumptions

In this section, we first explain our assumptions before describing the proposed IDMMAC protocol in detail.

- C number of non-orthogonal channels is available and all have the same bandwidth.
- C number of non-orthogonal channels is divided into a control channel and C-1 data channels. The control and data channels are used to transfer control and data messages, respectively.
- Each sensor node is equipped with a half-duplex transceiver and directional antenna. Hence, a sensor can either transmit or receive data only on a single channel at any time.
- The actor node is equipped with multiple radios and on each radio T number of half-duplex transceivers is available to transmit or receive data on T number of channels.

3.2 Network Model

A set of static sensors $S = \{s_1, s_2, \ldots, s_n\}$ are deployed uniformly in the physical location. The optimal number of mobile actors $A = \{a_1, a_2, \ldots, a_n\}$ are placed effectively to spread in the network area. The actors are placed using a k-hop independent dominant set algorithm [22]. Each actor is embedded with two radios for actor-actor and sensor-actor coordination, respectively. Each radio consists of T transceivers and a set of $C = \{c_1, c_2, \ldots, c_n\}$ non-orthogonal channels ($T < C$). It can transmit the data simultaneously to C nodes using C number of non-interference channels. But the sensor is enabled with a single radio and consists of a half-duplex transceiver. Hence, it can transmit or receive on a single channel at any time.

3.3 IDMMAC Protocol Framework

The IDMMAC protocol framework consists of six phases: sensor location identification, cluster formation, backup cluster head, channel assignment for sensor-sensor coordination, a contention-based MAC protocol, and channel selection for actor-actor coordination phase. The proposed framework is shown in Fig. 2. The sensor location identification phase is used to estimate the location of sensors with the help of a received signal strength identification (RSSI) mechanism. The cluster formation phase describes a two-level hierarchical clustering algorithm. The backup cluster head selection phase is used to select a BCH from the cluster members based on their residual energy and node degree. The channel assignment for the sensor-sensor coordination phase is used for a sensor to select a channel, which provides maximum capacity and PRR from the available channels. The contention-based MAC protocol resolves the collisions when using a particular channel. The channel selection for the actor-

actor coordination phase selects a minimum interference and maximum throughput channel for an actor to communicate with its neighbor actor.

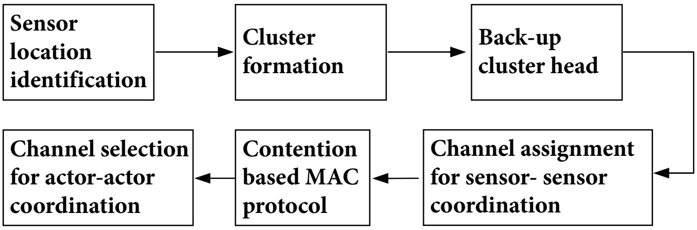


Fig. 2. Interference aware distributed multi-channel MAC (IDMMAC) protocol framework.

3.4 Sensor Location Identification

The location of a sensor can be computed with the help of a GPS device in a sensor, but this mechanism reduces the lifetime of the sensor. In the proposed IDMMAC protocol, a GPS device is only placed in the resource rich actors. Each actor forwards its position and ID to the sensors in its transmission range. The actor computes the sensor location using the RSSI technique. The received power at a distance d in free space model is computed as:

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi^2 d^2 L)} \tag{1}$$

where, P_t, $P_r(d)$ represents the transmission and received power for a distance d. G_t, G_r denotes the transmitter and receiver antenna power gain, respectively. λ represents wavelength, and L is the system loss factor. In the simulation G_t, G_r, and λ values are given as 1.

3.5 Cluster Formation

Fig. 3 shows a two-level hierarchical clustering architecture for WSAN [23]. In the first level, the actor acts as a cluster head for k-hop sensors. The sensors track the events and forward to an actor. Then, the actor executes reliable and timely actions on the event area based on the sensor's information. In the second level, the cluster head actors of the first level form a cluster and the sink acts as a cluster head for actors. The actors transfer the event information to the sink.

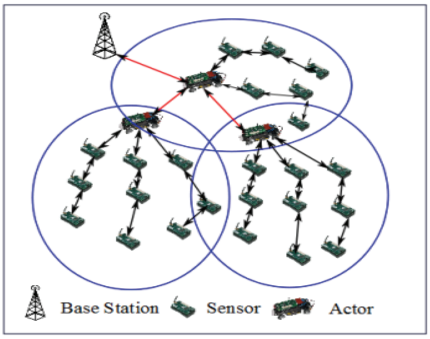


Fig. 3. Interference aware distributed multi-channel MAC protocol network architecture.

3.6 Backup Cluster Head

The backup cluster head setup phase will be enabled whenever a mobile actor leaves the cluster to help a neighbor actor or it is busy in performing actions in the event area. The BCH is selected among the cluster members based on their residual energy and node degree. The objective of electing a BCH is to minimize the overall energy spent in the network by reducing the cluster re-establishment process and to increase the packet delivery ratio. The actor elects one of its cluster members as a BCH based on the residual energy and node degree. The minimum threshold residual energy (E_{min}) is required for a cluster member to play the role of a BCH.

$$if\ \left(\left(E_{RE}(s_i)\right) \geq \left(E_{min}\right)\right)$$

then,

$$BCH\_Score = E_{RE}(s) * ND(s_i) \tag{2}$$

where, $E_{RE}(s_i)$ is the residual energy of the sensor s_i, *BCH_Score* is the suitability score of a cluster member to become a BCH, $ND(s_i)$ is the node degree of the sensor s_i. If all the cluster members do not meet the requirement, then the cluster re-establishment starts in the network. The newly elected BCH takes over the role of the cluster head and gathers data from its cluster members. After selecting a BCH, the actor broadcasts this information to the remaining cluster members using the common control channel. Then, the cluster members transfer their data to the BCH using intermediate sensors.

3.7 Channel Assignment for Sensor-Sensor Coordination

A multichannel MAC protocol should address the problems in channel assignment and medium access mechanisms. The former decides which channel is used by the node to communicate with its neighbor. The medium access mechanism resolves the collisions when using a particular channel. In WSAN, an ample amount of resource conservative sensors are available to sense the environment. Hence, a lightweight channel selection mechanism should be designed to enhance the sensor's lifetime. Two sensors in a cluster are called as ‘interfering’ if one sensor transmission interferes with the other. To eliminate the interference among sensors, every sensor should use a channel, which is different from its interfering sensors. In the proposed IDMMAC protocol, a lightweight channel selection mechanism is designed for sensor-sensor coordination. Each sensor selects a high capacity and PRR channel from among its available channels to communicate with its neighboring sensor. The PRR of a channel depends on the signal-to-noise plus interference ratio. As such, our proposed algorithm sensor considers the channel interference while selecting the channel to transfer data to its neighbor sensor.

According to Shannon’s theorem, the channel capacity does not only depend on its bandwidth, but it also considers the received signal strength and channel interference [24]. The maximum capacity that a channel c_k can provide between sensors s_i and s_j can be computed using the following equation:

$$MC^{c_l}_{s_i s_j} = Blog_2\left[1 + \frac{R^{c_l}_{y,s_j}}{GN + R^{c_l}_{I,s_j}}\right] \tag{3}$$

where, GN is the white Gaussian noise power, B is the bandwidth of the channel c_l, and $R^{c_k}_{y,s_j}$ is the received signal power by the sensor s_j. The $R^{c_l}_{y,s_j}$ value depends on the node density and probability of a sensor in an active state. The $R_{I,s_j}^{c_l}$ provides the interference information at the sensor s_j in channel c_l.

In the communication theory, the bit error rate (BER) is defined as the probability that a receiver fails to receive an incoming bit, because of signal to interference plus noise ratio (SINR). Unfortunately, the BER-SINR cannot be measured directly on radio transceivers [25]. Hence, recent studies [26] used a PRR with an SINR model. PRR is defined as the probability that a receiver successfully receives all of the bits in an incoming packet and it can be computed as:

$$PRR_{s_j}(p) = pr_{s_j}(p)^{x(p)} \tag{4}$$

where, $pr_{s_j}(p)$ is the probability that sensor s_j receives an incoming bit of packet p of size $x(p)$. The $pr_{s_j}(p)$ depends on the energy of the signal E, and the two-sided power spectral noise density $N/2$.

For IEEE 802.15.4 radio's, the $pr_{s_j}(p)$ is computed as:

$$pr_{s_j}(p) = 1 - Z\left(\sqrt{\frac{2E}{N}}\right) \tag{5}$$

$$Z(x) = \frac{1}{\sqrt{2\pi}}\int_y^\infty e^{-t^2/2} dt = \frac{1}{2}\left(1 - gef\left(y/\sqrt{2}\right)\right) \tag{6}$$

where, *gef*() is the Gaussian error function. The SINR at the receiver of packet p is given as:

$$\emptyset = \frac{E}{GN}\frac{M_R}{N_B} \tag{7}$$

where, M_R is the modulation rate and N_B is the noise bandwidth. Eq. (8) is derived by substituting Eq. (5) with Eq. (7) in Eq. (4).

$$PRR_{s_j}(p) = \left(\frac{1}{2} + \frac{1}{2}\left(gef\left(\sqrt{\frac{N_B\emptyset}{M_R}}\right)\right)\right)^{x(p)} \tag{8}$$

3.8 Contention-Based MAC Protocol

The interference-free channel assignment cannot resolve contention caused by the sensors. If two sensors want to communicate with the same destination sensor, then it will cause collisions in their data. Hence, a contention-free or contention-based MAC protocol is required to reduce the collisions. The contention-free MAC protocol requires tight time synchronization, which creates a lot of burden on resource conservative sensors and provides fewer throughputs under low traffic conditions. Hence, the proposed algorithm uses the contention-based MAC protocol. If two sensors want to communicate to a common parent, then the sensor that wins the contention phase transfers its data to the parent node. The CSMA/CA mechanism is used in the contention phase. The control messages are transferred using the common control channel to increase network performance. If a sensor does not have data to transmit, then it will go into the sleep state and forward its sleep duration to its 1-hop neighbors. The sleep period reduces energy consumption and idle listening in the network.

In the IDMMAC protocol, time is divided into beacon intervals. Each beacon interval is further divided into the ATIM window and data transmission phase. Whenever a sensor wants to transmit data, it selects a maximum PRR and capacity channel in the ATIM window phase. The channel negotiation between source and destination is done via the common control channel. During the ATIM window, each sensor should listen to the control channel and send its control messages using the control channel. When a node *u* wants to transfer data to *v*, it senses the control channel. If the channel is idle for a distributed inter frame spacing (DIFS) time, then the node *u* generates a random back-off time from the range [0, cw-1], where cw is the size of the contention window. After the back-off timer reaches zero, the node *u* sends a RTS packet. In the RTS phase, the sensor *u* sends information about the channel, which consists of a maximum PRR and capacity channel. In the case of actor maximum throughput and a minimum interference channel with respect to the destination *v* among the available channels. After receiving the channel information, node *u* sends a CTS packet to *v* and switches to the selected channel to receive data from *u*. This contention-based mechanism reduces the number of collisions and selects a minimum interference channel from out of the available set of channels.

3.9 Channel Selection for Actor-Actor Coordination

A delay-aware MAC protocol is required for actor-actor coordination in WSAN. Energy is not an important parameter when designing a multichannel MAC protocol for actor-actor coordination, because the actor is a resource-rich node. Hence, a throughput and interference-based MAC protocol is designed for actor-actor coordination. Every actor is embedded with two radios for sensor-actor and actor-actor coordination. Hence, the data transmission in the sensor-actor phase does not interfere with the actor-actor coordination. In this proposed multichannel MAC protocol, an actor selects a minimum interference and maximum throughput channel from amongst the available channels. This mechanism finds a better non-interference channel from the source to the destination and increases the network performance.

Let us consider an actor a_j that receives data from actor a_i over channel c_l. The throughput for channel c_l from actor a_i to a_j is calculated as:

$$\varphi_{a_i a_j}^{c_l}(t) = \frac{AG_{a_i} \emptyset_{c_l} Z_{c_l} \left(1 - Q_{c_l}\right)}{\sum_{T=0}^{n} \emptyset_T Z_T (1 - Q_T)} \tag{9}$$

where, $\varphi_{a_i a_j}^{c_l}(t)$ denotes the throughput of channel c_l between actors a_i and a_j at time t and AG_{a_i} denotes the aggregated throughput at actor a_i. The $\emptyset_{c_l}$ represents the service probability of channel c_l and Q_{c_l} represents the channel loss probability in the network.

The service probability of the channel c_l is calculated as:

$$\emptyset_{c_k} = \frac{\omega_{c_l} MC_{c_l}}{\sum_{c_k=0}^{n} \omega_{c_l} MC_{c_l}} \tag{10}$$

The ω_{c_l} provides the window size at the back-off time t using IEEE 802.11 and MC_{c_l} calculates the maximum capacity of channel c_l. The maximum capacity that channel c_l can provide between actor a_i and a_j is calculated using Eq. (11).

$$\lambda_{a_i a_j}^{c_l} = \frac{1}{N_i * M_{a_i a_j}} \sum_{c_l \in C} D_{c_l} + \sum_{c_l \in C} J_{c_l} \tag{11}$$

where, $\lambda_{a_i a_j}^{c_l}$ provides the minimum interference channel, if this value is close to zero. Then, it indicates that channel c_l has less interference from its neighbors. N_i represents the neighbor set of actor a_i, which is useful to calculate the interfering actors with a_i during data transmission on channel c_l. $M_{a_i a_j}$ is the expected transmission time (ETT) between a_i and a_j, D_{c_l} represents the interference aware resources for channel c_l, and J_{c_l} defines the channel switching cost.

The ETT between actor a_i and a_j is calculated as:

$$M_{a_i a_j} = \frac{1}{(1-p)} * \frac{S}{B} \tag{12}$$

where, p denotes the probability of an unsuccessful transmission, S and B represent the prob packet size and bandwidth of channel c_l.

$$p = 1 - (1 - p_f)(1 - p_r) \tag{13}$$

where, p_f and p_r denote the probability of packet loss in the forward and reverse directions. The interference aware resources (D_{c_l}) for channel c_l is estimated as:

$$D_{c_l} = M_{a_i a_j} * N_i \tag{14}$$

The channel switching cost is calculated as:

$$J_{c_l} = w_1 if\ ch(prev(i)) \neq ch(i)\ else\ J_{c_l} = w_2 \tag{15}$$

where, w_1 and w_2 are the constants. $0 < w_1 < w_2$. $ch(i)$ is the channel assignment of node i and $ch(prev(i))$ represents the channel assignment for the previous node of i along path p.

The channel selection mechanism for actor-actor coordination calculates the channel interference level using ETT. The ETT calculation consumes lot of energy, but gives accurate results in the channel interference level. Hence, it is used in actor-actor coordination, because actors are resource-rich nodes.

4. Experimental Setup and Analysis

The performance of the IDMMAC protocol is evaluated using the NS2 simulator. Each sensor is enabled with a single radio and directional antenna. The actor is embedded with two radios for sensor-actor and actor-actor coordination. Multiple transceivers and omnidirectional antenna are enabled on each radio for an actor. The simulation parameters are listed out in Table 1.

Fig. 4 describes a simple radio model, which is used in our simulations for energy dissipation in the sensor networks. The free space (d^2 power loss) and the multipath fading (d^4 power loss) channel models are used based on the distance between the transmitter and receiver. The free space model is used if the distance is less than threshold d_o; otherwise, a multipath model is used. The cost to transfer a b-bit message

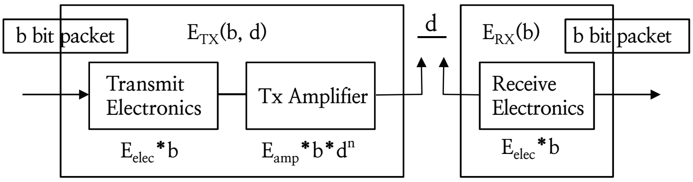


Fig. 4. Radio energy dissipation model.

for distance *d* is computed as:

$$E_{TX}(b) = E_{Tx-elec}(b) + E_{Tx-amp}(b, d)$$

$$\begin{cases} bE_{elec} + bE_{fs}d^2, d < d_o \\ bE_{elec} + bE_{mp}d^4, d \geq d_o \end{cases} \tag{16}$$

where, $d_o = \sqrt{\frac{E_{fs}}{E_{mp}}}$ E_{fs}, E_{mp} represents the energy dissipated for each bit in the free space and multipath model, respectively. $E_{Tx-amp}(b, d)$ is the energy required for the amplifier to amplify *b* bits to distance *d*. The energy dissipated to receive the message is computed as:

$$E_{RX}(b) = E_{RX-elec}(b) = bE_{elec} \tag{17}$$

The electrical energy E_{elec} is based on the signal coding, modulation, and filtering mechanisms. The amplifier energy, $E_{fs}d^2$ or $E_{mp}d^4$ depends on the receiver distance and noise ratio. In our simulations, the optimal number of actors is computed as:

$$A_{opt} = \sqrt{\frac{N_o}{2\pi}}\sqrt{\frac{E_{fs}}{E_{mp}}}\frac{L}{D_{toBS}^2} \tag{18}$$

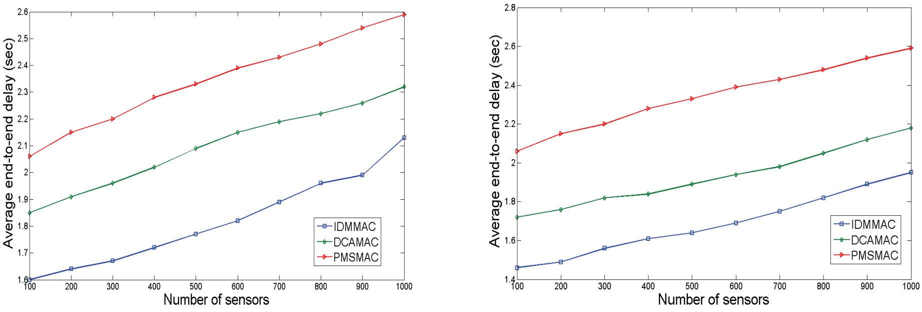
N_o represents the number of sensors, *L* is the network area, and D_{toBS} is the mean distance from the actor to the sink.

Table 1. Simulation parameters

Parameters	Values
Simulation duration	300 s
Traffic flow	CBR
Mobility pattern	Random waypoint
Sensor's transmission range	100 m
Actor's transmission range	300 m
k	3
Sensor's initial energy	2 J
Packet size	512 B
ATIM window size	20 ms
Beacon interval	100 ms
Data transfer rate	20-60 pkts/s
Number of channels	3-4
E_{fs}	10 pJ/bit/m^2
E_{mp}	0.0013 pJ/bit/m^4
E_{elec}	50 nJ/bit

4.1 Simulation Results

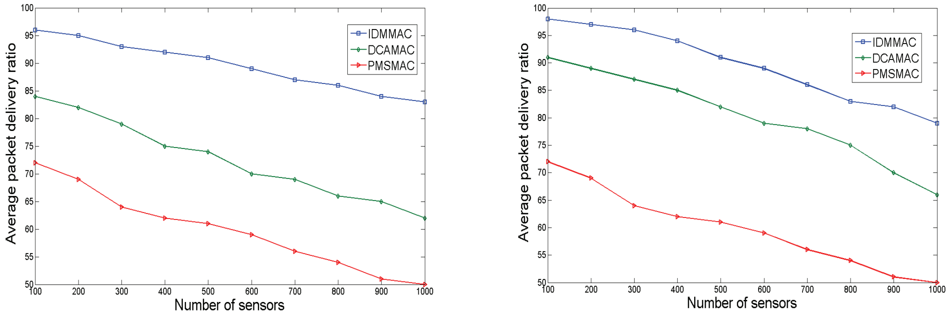
Fig. 5(a) and (b) represent the average end-to-end delay with a variable number of sensors for 3 and 4 channels, respectively. The number of actors is also increased linearly with the increase in the number of sensors. In IDMMAC, the contention between intra-subtree sensors is minimal. But the inter-subtree contention still exists and it is tried to reduce with the contention-based MAC protocol. Hence, the proposed IDMMAC protocol performs well compared to the existing MAC protocols. The simulation results indicate that the average end-to-end delay increases with the network density and it is indirectly proportional to the number of channels.



(a) (b)

Fig. 5. Average end-to-end delay for (a) 3 channels and (b) 4 channels.

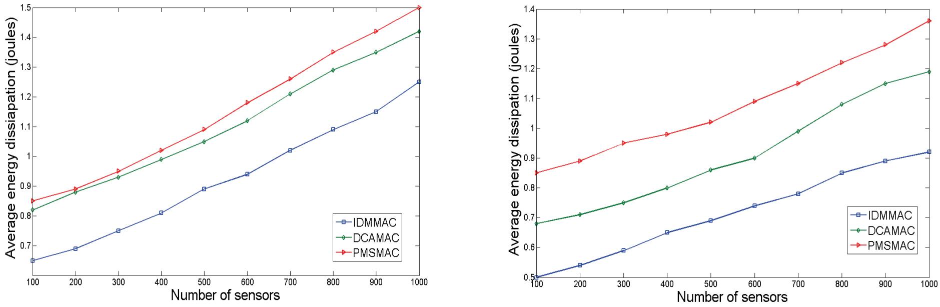
Fig. 6(a) and (b) represent the average packet delivery ratio in the network for a variable number of sensors with 3 and 4 channels, respectively. It is defined as the number of packets that are 512 bytes in size that are successfully delivered from the source to the destination. In WSAN, the packet delivery ratio depends on the channel quality and congestion in the network. The IDMMAC protocol reduces network congestion by transferring data through multiple channels. The channel is selected dynamically based on its interference level. The control and data packets are transferred using the control and assigned data channels, respectively. The actor is enabled with T transceivers; hence, it can receive packets from T channels at the same time. The packet delivery ratio is decreased with the increase in network density and it is directly proportional to the number of channels. The results indicate that the proposed IDMMAC protocol performs well compared to the existing protocols.



(a) (b)

Fig. 6. Packet delivery ratio for (a) 3 channels and (b) 4 channels.

The average energy dissipated in the network is defined as the mean amount of energy consumed to establish the communication and transfer the data. WSAN consists of a large number of battery-constrained sensors, so it is important to design an energy-efficient MAC protocol. In IDMMAC, the sensor goes into a sleep state whenever it does not have any data to send. The actor performs the energy-consuming tasks, such as shortest path calculation and channel allocation, for all the sensors. A lightweight channel selection is also proposed to improve the sensor's lifetime. Hence, the average amount of energy consumption in the network for the IDMMAC is less as compared to the existing MAC protocols. Fig. 7(a) and (b) indicate that the average energy consumption increases with the increase in network density and it is inversely proportional to the number of channels.



(a) (b)

Fig. 7. Average energy dissipation for (a) 3 channels and (b) 4 channels.

5. Conclusion

In the IDMMAC protocol, a lightweight channel selection mechanism has been designed for sensor-sensor coordination. Each sensor selects a maximum PRR and capacity channel from amongst its available channels to transfer data to the actor. It achieves better energy efficiency because of sensor sleep and lightweight channel selection mechanisms. To avoid the multichannel hidden terminal problem, every node listens to the default control channel at the start of each time slot. A contention-based MAC protocol is also proposed to reduce the contention amongst sensors while transferring data to the same sensor. Furthermore, an interference and throughput aware multichannel MAC protocol is also proposed for actor-actor coordination. The actor selects a minimum interference and maximum throughput channel from among the available channels to communicate with the destination actor. To evaluate the performance of the proposed IDMMAC protocol, it was simulated using NS2. The results were analyzed using various QoS parameters; namely, packet delivery ratio, end-to-end delay, and energy dissipation in the network. The simulation results indicate that the IDMMAC protocol performs well compared to the existing MAC protocols.

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