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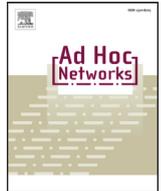
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Dynamic Neighbour Aware Power-controlled MAC for Multi-hop Ad-hoc networks

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ABSTRACT

In Ad-hoc networks, resources in terms of bandwidth and battery life are limited; so using a fixed high transmission power limits the durability of a battery life and causes unnecessary high interference while communicating with closer nodes leading to lower overall network throughput. Thus, this paper proposes a new cross layer MAC called *Dynamic Neighbour Aware Power-controlled MAC (Dynamic NA-PMAC)* for multi-hop Ad-hoc networks that adjust the transmission power by estimating the communication distance based on the overheard signal strength. By dynamically controlling the transmission power based on the receivable signal strength, the probability of concurrent transmission, durability of battery life and bandwidth utilization increases. Moreover, in presence of multiple overlapping signals with different strengths, an optimal transmission power is estimated dynamically to maintain fairness and avoid hidden node issues at the same time. In a given area, since power is controlled, the chances of overlapping the sensing ranges of sources and next hop relay nodes or destination node decreases, so it enhances the probability of concurrent transmission and hence an increased overall throughput. In addition, this paper uses a variable backoff algorithm based on the number of active neighbours, which saves energy and increases throughput when the density of active neighbours is less. The designed mechanism is tested with various random network scenarios using different traffic including CBR, Exponential and TCP in both scenarios (stationary and mobile with high speed) for single as well as multi-hop. Moreover, the proposed model is benchmarked against two variants of power-controlled mechanisms namely *Min NA-PMAC* and *MaxRC-MinDA NA-PMAC* to prove that using a fixed minimum transmission power may lead to unfair channel access and using different transmission power for RTS/CTS and Data/ACK leads to lower probability of concurrent transmission respectively.

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1. Introduction

In shared bandwidth Ad-hoc networks, interference is a significant limiting factor in achieving high network performance. Since interference range is directly proportional to transmission range, controlling transmission power of active nodes dictates the density of parallel or simultaneous communication. In such networks, using a large transmission power may reduce the number of hops between the source and destination and increases a per-flow throughput in absence of other contending data flows.

However, high transmission power increases an overall interference level, so the chances of concurrent transmission reduce extensively and an overall network performance degrades when the number of active nodes in such network increases. On the other hand, when the transmission range is low, the overall interference decreases but the number of hops between the source and the destination increases in a multi-hop environment. As a result, the end-to-end per-flow throughput may decrease [1], but the reuse factor in terms of frequency and space increases, eventually the probability of concurrent transmission increases, resultant in a higher overall network performance. In a shared channel, when nodes are within each other's interfering ranges, only one node can transmit in presence of other nodes. When a pair of communicating nodes is closer, using a maximum fixed transmission power may lead to unnecessary interference to other nodes and wastage of energy, as shown in Fig. 1(I). Given the same topology, if a node communi-

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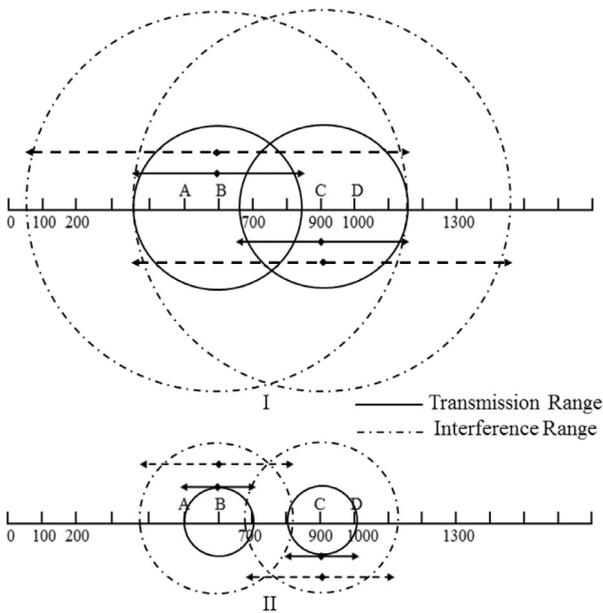


Fig. 1. (I) Sharing channel by using a fixed transmission Range (II) concurrency achieved by using an estimated power-controlled transmission.

cates with the next hop destination using only the required minimum transmission power as shown in Fig. 1(II), then the area of interference decreases and exhibits a higher probability of concurrent transmission and prolongs the battery life. However, the authors of [2] presented that in an optimal power control mechanism approaches to improve spatial utilization, senders should not send with just enough power to reach the next hop node, but use a higher transmission power and their claim is reinforced in this study because using a minimum transmission power may be affected and limited by other active neighbours and external factors including other signals and its environment condition.

Therefore, the paper aims to control the transmission power to reduce the interference level and increase the probability of concurrent transmission to gain overall network performance and save battery life. In this paper, in order to take advantage of using a maximum transmission to reduce path lengths, route discovery is conducted using maximum transmission power and a newly estimated power is used to deliver both control as well as data frames to provide a scope of concurrent transmission made the study unique. Moreover, the paper conducts a detail study on both static as well as dynamic Ad-hoc networks with single and multi-hop path, where nodes move with high speed and inspect the probability of concurrent transmission and study an effect on battery life and per-flow fairness through extensive simulation using various possible network setups.

In our previous work, in order to estimate the required power between a source node or a relay node to the next hop, a location based power-controlled MAC is designed in [3] where the location information is used to estimate the distance between the communicating nodes. However, location information is not readily available, so such an approach is invalidated if nodes are not provided with location information or if nodes cannot acquire location information. The work of [3] is extended in [4] by tuning the transmission power based on the activity of its neighbours and developed a technique to defer channel access dynamically based on the length of the busy state of the shared channel to avoid hidden node issue and ensure a fairer channel access. However, the study of [4] was developed only for a single hop environment by assuming that the location information was provided during initial node deployment and the study did not consider multi-hop communication with node mobility. In order to avoid such limitations,

in this paper, location information is not used; rather transmission power is derived from the received signal strength and its initial power. In addition, the transmission power is dynamically adjusted by considering neighbour's signal strength to avoid hidden node situations. In both [3] and [4], the backoff mechanism based on the number of active neighbours was introduced, but the analysis of the energy consumption during the backoff periods was not highlighted, so this paper extends the study and incorporates the study of the amount of energy utilization during such deferring sessions.

In summary, the main contributions of this paper are as follows:

- Avoids discovering route with a path of higher hop count by using a fixed transmission power (because lower transmission power leads to higher number of hops to reach the destination). Higher path length lowers throughput in a multi-hop network, so avoiding high hop path is critically necessary during controlling power.
- Increased the probability of concurrent transmission by dynamically controlling sender's transmission power (per-frame) based on the received signal strength and neighbour's transmission power and saves energy and reduces unnecessary interference. This approach reduces or avoids hidden node issues by using an optimal transmission power. Thus, the actual control of transmission power is activated only after route discovery, making the approach novel and unique.
- During channel contention, in order to accurately defer channel access and reduce unnecessary waiting time, a backoff mechanism based on the number of the active contenting neighbours is used.
- Finally, the contribution of this paper includes a study of the impact of network performance and battery life in a *highly mobile network settings* in a *multi-hop* network environment and compared the propose model with a minimum transmission power mechanism, fixed transmission power mechanism and a mechanism which uses varying transmission power depending on packet type unlike many authors who tend to focus only on single hop or stationary multi-hop network.

The remainder of the paper is structured as follows. In Section 2, some related works on power control transmission are discussed. The proposed power-controlled MAC is described in detail in Section 3. Section 4 provides the evaluation of the results, and then Section 5 concludes the paper by proposing a number of future directions.

2. Related transmission power control in Ad-hoc networks

Many power-controlled transmissions have been proposed in literature, which generally adopt a method of using different transmission power depending on frame types, setting different power levels and some uses contention level based. All the authors aim to avoid or reduce interference and increase concurrent transmission to improve the overall network performance, but majority do not study the overall impact on battery life and high mobility scenarios by focussing only on overall network performance which is not the case in this paper. A power-controlled MAC for single channel is discussed in [5] and [6], where the authors use the RTS and the CTS control frames for advertising the signal strength and exchanges N number of RTS/CTS pairs for securing N concurrent transmissions. However, such approach involves a significant high control overhead. In order to reduce the signaling burden, authors of [7] proposed an adaptive power control MAC by using only the RTS and CTS for collecting transmission power of the active neighbours and interference level. However, the study assumes that the transmission range and the carrier

sensing range are identical, which is rather artificial as the carrier sensing range is typically greater than the transmission range. Moreover, such approaches use a maximum transmission power for RTS and CTS control frames and used minimum power for Data and ACK frames as that of the mechanisms proposed by authors of [8–10]. Other mechanisms which use varying transmission power depending on frame types are also highlighted in [11–13]. The authors of [14] developed a power-controlled transmission technique by sending control messages containing the transmission power information using a maximum transmission power in the Announcement Traffic Indication Message (ATIM) window, but again the data packets are sent using a minimum required transmission power by checking if a neighbour node will allow a concurrent transmission. However, in all such approaches, while achieving their aim of reducing an interference range while sending RTS or CTS or Data frames, it has an inherent limitation, because the overall probability of concurrent transmission is extensively affected, since the frame using high transmission power will always reduce the probability of concurrent transmissions and this paper addressed this issue by comparing with one such work in detail. To reduce the degree of collision in such approaches, a new power-controlled MAC is proposed in [15] which utilizes the fragmentation mechanism of IEEE 802.11 MAC and controls the transmission power based on the fragmentation technique. In such mechanism, all the RTS, CTS and ACK frames corresponding to fragmented data frames are sent with maximum transmission power except the last one, to reduce collision with the surrounding active neighbours. However, in reality fragmentation does not occur unless the frame size crosses the Maximum Transfer Unit (MTU) of the link.

The authors of [16] used different approach in controlling transmission power by considering a set of power levels, starting with a low transmission power while discovering or sending data to the next hop node. If the next hop node is unreachable, a higher level of transmission power is considered until the next hop node is discovered or until it reaches the highest possible transmission power level, whichever is earlier. However, the limitation of such technique is that each node will try with different transmission power levels without knowing whether it will result in successful discovery or sending data to the next hop node. A cross layer technique combining scheduling, routing and power control transmission is proposed in [17], based on the Time Division Multiple Access (TDMA) mechanism. However, using deterministic access mechanisms in a distributed Ad-hoc networks is highly challenging due to synchronisation issues when the number of the participating nodes in the network changes (leave, died or join) and allocating access timing slots to nodes that have no data to send is ineffective while other waits for their chance to access.

A power control transmission based on the interference and distance estimation is designed in [18], but such an approach suffers from distinguishing the differences between the low power transmissions of short distances from high power transmission with long distances. There are other authors focussing on controlling transmission power based on the degree of contention, like the one designed in [19] and [20], however in such approach it is vital to know how much to decrease to reduce overlapping and if there is less contention then using a higher transmission may still lead to lower chances of concurrent transmission because of sharing channel. So, in this paper when contention increases, the transmission power is re-estimated by considering neighbour's transmission power to avoid hidden node issue. In a power-controlled transmission, due to use of different transmission power, the chances of hidden node issue increases, so the authors of [21] suggest to increasing the carrier sensing range of the receiver depending on the transmission and interference range of the sender. In fact, in a distributed and a dynamic network, to obtain an optimal transmission power is an NP-hard problem even

if a node has the entire knowledge of the network as highlighted by the authors of [22], because any node could join the network, leave the network, or can be in motion at random speed. So, there are authors who tried to take different approach and rather control the network topology by considering the interference level experienced by a node and one such is designed by the authors of [23], but its easy when nodes are stationary, otherwise its complex is manifold when nodes are dynamic. Therefore, considering the complexity involved in eliminating the hidden node issues and in choosing an optimal transmission power, this paper observe the activity of neighbour's transmission power to derive the best transmission power pertaining to the neighbourhood to reduce or avoid hidden node, saves energy and try to provide concurrent transmission if possible to enhance the overall network performance. Thus, majority of the existing work focussed on using maximum transmission power for control frames like RTS/CTS and low transmission power for Data/ACK by focussing only at the activity of data link layer i.e. layer 2, but the aspect of hop count and path length of a route of layer 3 is not addressed even though it has a direct correlation with the end-to-end network performance. Therefore, in this paper adaptation of transmission power is carried out by considering the activities of both layer 2 and layer 3.

3. Proposed power control cross layer

As addressed by prior research work, the transmission power does have a significant influence on the network capacity, particularly for high node density, due to the high degree of transmission and interference overlapping. So, this paper proposes a new cross layer MAC called *Dynamic Neighbour Aware Power-controlled MAC* (Dynamic NA-PMAC) for a multi-hop Ad-hoc networks where transmission power is adapted by considering node's activity, neighbour's transmission power and frame type (Routing frame or Data frame or RTS or ACK). The transmission power is adjusted based on the received signal strength, estimated communication distance and the overheard signal strength of the neighbours. The designed protocol consists of the following four parts:

- i Discovering the path using a fixed maximum transmission power, so that the path length is not compromised during route discovery because low transmission power leads to high hop path and the end-to-end throughput is inversely proportional to path length in multi-hop Ad-hoc networks [1]. The approach guarantees a path with a low hop count. After, route is discovered; transmission power is controlled during data and control frame transmission to provide a scope of probable concurrent transmission.
- ii The transmission power between two consecutive nodes is estimated by considering the received signal strength and the corresponding original sender's transmission power.
- iii The transmission power is dynamically adjusted based on node's status (static or mobile) and neighbour's signal strength because received signal strength changes depending on node's status.
- iv Lastly, the MAC protocol uses a new random backoff values based on the number of active neighbours instead of using a fixed range of backoff values.

The study considers a perfect channel, however being a wireless channel the signal may fluctuate and can be affected by unknown external environmental factors, so in this paper instead of using a minimum power to cover the communicating distance (d), the power of transmission is calculated to cover $d + \Delta$ in order to account for fading or shadowing effect, where Δ is only 1% of d , because of considering a perfect channel condition. Detail assumptions are listed in Section 3.1 and power control estimations are elaborated in Section 3.2 in detail. The proposed protocol is tested

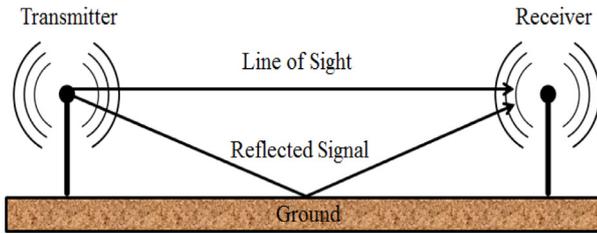


Fig. 2. Two ray ground propagation model.

against a fixed transmission power like IEEE 802.11b, and a variants of power-controlled based MACs such as MaxRC-MinDA NA-PMAC, where the RTS and CTS are sent with maximum transmission power ($Power_{Max}$) and the Data and ACK are sent with minimum transmission power. This approach is like that of the study conducted in [11,12, and 13]. The proposed mechanism is also compared with Min NA-PMAC, where the RTS, CTS, Data, and ACK are all sent using an estimated minimum power. The method of using minimum power is similar to that of the paper designed in [3].

3.1. Assumptions considered for the wireless model

As described by the authors of [24], this work also follows a simple wireless communication model with a perfect radio propagation channel as used in academic practice with the following assumptions:

- i The surface of communication is flat.
- ii A radio's transmission area is circular.
- iii If node A can hear node B, then node B can also hear node A (symmetry), when nodes don't move and use same transmission power.
- iv If node A can hear node B at all, node A can hear node B perfectly.
- v Signal strength is a function of distance.

In this study, a perfect radio propagation channel is considered and used a Two Ray Ground propagation model because the authors of [25–27] concluded that for a very short distance communication, Friis propagation model is ideal due to the consideration of the line of sight signals, however for a longer distance communication, Two Ray Ground propagation model is more efficient because it takes into account both the reflected as well as the line of sight signals. However, in a real environment, the received signal strength may not be a deterministic function of a distance because of the multipath signal propagation effect, external environmental factors, and obstructions. However, the study is considered to be taking place in ideal open space and it does not consider external obstructions like trees, building, and other heavy objects, so the propagation model can handle obstruction better due to consideration of both line of sight and reflected signals. Moreover, the focus of the study is on the probability of concurrent transmission and energy usage in a powered controlled transmission in a multi-hop environment (*static and highly mobile nodes*) and not on effects upon signals due to environmental factors.

The Two Ray Ground propagation model is shown in Fig. 2, where both the reflected signals as well as the strong line of sight signal are taken into account, so it can handle the issue of obstruction better. However, the issue of field strength variations of the signal when the antenna is displaced for a large distance is not considered due to the assumption of a perfect channel condition, but channel fading over a distance is considered. Moreover, in this study, only the interference caused by other active nodes of the network is considered, so interference caused by other external environmental factors is not taken into account. However, in

case of overlapping multiple signals, frame loss due to collision is considered unless SNR is at least ten times higher. The mechanism uses a distance path-loss component, but the reception decision is based on the threshold of the receiving signal strength called *RX-Thresh*. During simulation and testing, it is assumed that packets generated by any source are of same size and it is considered to be 1000 bytes.

In analysing the network performance of the designed mechanism, the maximum transmission power considered for each node is $P_{max} = 24.49$ dBm; this power value can cover a maximum fixed transmission range of 250 m (default standard values as described in NS2 for a fixed transmission range). The interference range is always higher than the transmission range and as per the default standard value described in NS2, its radial distance is 2.2 times that of the transmission range. As a result, when a node sends Data with a transmission power of 24.49 dBm, the transmitting node covers an interference range of approximately 550 m. Moreover, when the received signal strength crosses the threshold signal strength of -64.37 dBm then it is considered to be within a transmission range and any measured signal strength up to -78.07 dBm is considered to be within its interference range.

The detailed work of the proposed power-controlled cross layer MAC is described in the following subsections. Section 3.2 describe how a node calculates and control the transmission power and adjusts transmission power based on the type of frame (routing frames, data frames and control frames like RTS-CTS-ACK) and the transmission power experienced from its active neighbourhood.

3.2. Estimation and control of transmission power

The uniqueness of this paper is that the mechanism allows the initial route discovery to take place using a maximum transmission power and controls the transmission power thereafter during the transmission of control and data frames as highlighted earlier in Section 3 to ensure shorter route and increase the probability of concurrent transmission. The estimation of the transmission power varies depending on the presence or the absence of other active neighbour nodes. In presence of other active neighbour node(s) the transmission power is estimated considering the transmission power of its neighbourhood.

3.2.1. Estimation of transmission power in absence of other active neighbours

In order to achieve the proposed technique, the model modifies the RTS and CTS control frames by introducing new fields to exchange the initial transmission power information to help estimating the required signal strength. When a relay or destination node (say) node B receives the first RTS control frame from a source node (say) node A using a maximum transmission power ($Power_{Max}$) irrespective of the communicating distance between them and the intended receiver node B extracts the transmission power of the source node from the RTS frame and measures the received signal strength (P_r) at the receiving node B to calculate a new required power to transmit. This new transmission power is strong enough to communicate and covers $d + \Delta$, where d : the distance between the source node and the next hop destination node as shown in Fig. 3. The distance (d) between the communicating node A and B is calculated using (2) of The Two Ray Ground propagation model. Then the destination node replies a CTS control frame to the source node with the newly estimated transmission power and the estimated power is used to communicate between the two communicating pair until the node moves and a different transmission power is required. The destination node B calculates the power of transmission (P_t) using (1) to cover the distance ($d + \Delta$), so that the receiver receives a signal strength of at least

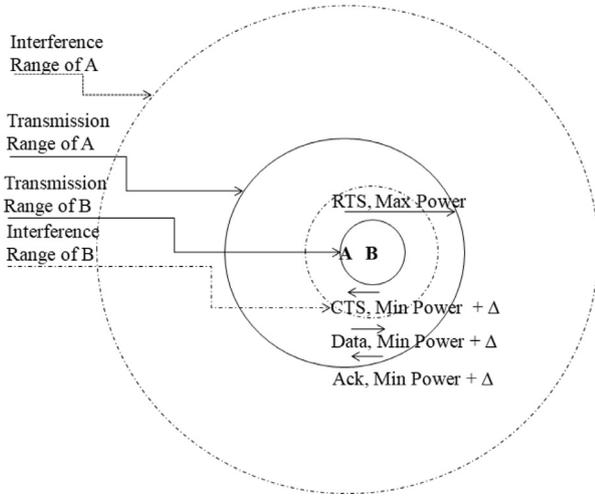


Fig. 3. Power adaptation when first RTS and CTS are exchanged.

the threshold value $P_{thresh} = -64.37$ dBm to make the data decodable. The factor of $+\Delta m$ enables the communicating nodes to accommodate any loss in signal to maintain the minimum receivable signal threshold, since the path loss is also dependent on other factors like multipath signal effects and the environment in which the network is deployed, but here in the study since a perfect channel condition is considered, so there will be no effect. Thus, the source node and the next hop destination uses the newly calculated transmission power (P_{est}) for sending the control frames and the data frames unless any of the participating node moves and a different transmission power is required or a stronger signal strength is experienced from around the neighbourhood. Therefore, the entire process helps in saving energy and extends battery life and increases the probability of concurrent transmission as highlighted in Fig. 1(II), when the next hop or destination is located nearer to the source or a relay node. In addition, a source node communicates by taking into account a higher transmission power, if it exists within its neighbourhood, then the issue of hidden nodes is expected to be avoided or reduced. In order to record source node's activity and neighbour's activities, each node maintains two tables entry namely $Table_{Out}$ and $Table_{In}$ to capture the outgoing activities and the incoming activities respectively. The table $Table_{Out}$ has two fields namely: Sender's transmission power (P_t) and Destination ID and $Table_{In}$ stores the newly estimated transmission power (P_{est}) based on the incoming signal strength and the Source's ID.

$$P_t = P_r d^4 L / G_t G_r h_t^2 h_r^2 \quad (1)$$

$$d = \sqrt[4]{(P_t G_t G_r h_t^2 h_r^2) / (P_r L)} \quad (2)$$

3.2.2. Estimation of transmission power in presence of other active neighbours

When a node experience a higher transmission power from its neighbourhood, it's vital to re-estimate the transmission power, otherwise as shown in Fig. 4, node C and node D will be hidden from the activity of node A and node B because of using low transmission power while node A and node B uses a much higher transmission power due to their distance of communication. As a result, the activity of node C is directly interfered by the activity of node B and fair contention is not possible since node B is out of the transmission range of node C. In order to resolve such partial hidden nodes issue, the proposed mechanism consider the signal strength of the transmission power of the active neighbour nodes and when its current transmission power is lower than its neighbour's transmission power, it adapts to the transmission power that would

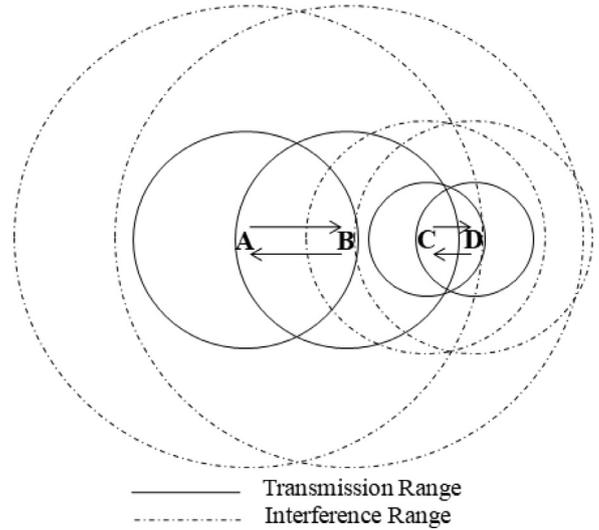


Fig. 4. Transmission power estimation without neighbour's power consideration.

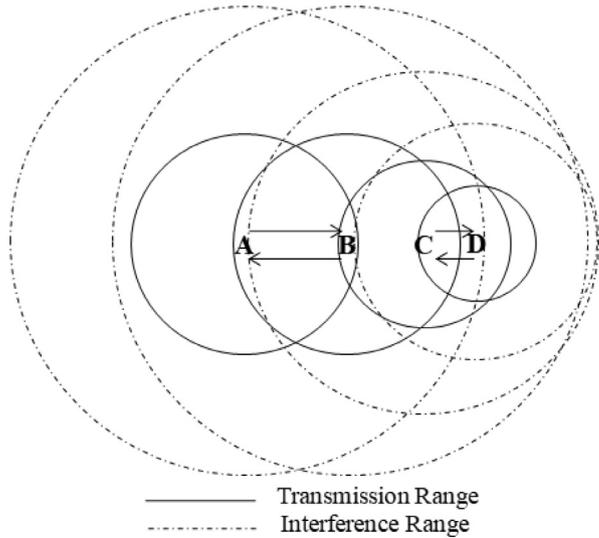


Fig. 5. Transmission power estimation by considering neighbour's transmission power.

cover the neighbour with higher transmission power to avoid partial hidden node issues as shown in Fig. 5, where node C increases its transmission power to avoid being a hidden node to node B and uses an optimal transmission power i.e. OP_{est}^i for achieving a fairer contention among node B and node C. However, node D can continue communicating with node C using the transmission power to cover node C. Thus, when node i (using Est_{P_t} as transmission power) is surrounded by other active neighbour nodes (say) $\{k, l, m, \dots, n\}$ which uses varying transmission powers (say) $\{P_k, P_l, P_m, \dots, P_n\}$ respectively depending on node's positions, then a $\text{Max}\{Est_{P_t}, P_k, P_l, P_m, \dots, P_n\}$ is considered as an optimal transmission power (OP_{est}^i) for node i to reduce or avoid hidden node issue. The issue of hidden node cannot be solved completely especially when transmission power is controlled and when the active nodes uses varying transmission power based on the closeness between a source and a next hop node, however it can be aimed to reduce the number of the affected nodes by estimating a transmission power by taking into account the signal strength of the active neighbours.

In case, when the power-controlled mechanism is invoked and if the communicating pairs of the neighbourhood do not fall within the sensing range of each other like the communicating pairs of

node (A and B) and node (C and D) of Fig. 1(II), then concurrent transmission is achieved and the network performance is enhanced by the number of concurrent transmission pairs and saves battery life at the same time for not using a high transmission power while communicating closer next relay node or a destination node. The detail algorithm for estimating and adjusting transmission power is described in Table 1.

3.2.3. Algorithm for recording neighbour's transmission power

Every node i.e. both active as well as passive nodes record the activities of the overheard RTS and the CTS control frames to help in estimating an optimal transmission power. Table 2 describes the detailed algorithm on how a node captures and maintains the transmission power information of its neighbours. The first overheard RTS frame from the neighbour node i is ignored, because subsequent communication does not use maximum transmission power ($Power_{Max}$), rather the newly estimated transmission power ($EstPt$) is used. The node overhearing the neighbour's activity records the IDs of the source and the destination pair, timestamp, NAV and the transmission power. If the frame is not intended for the node, then the node backs off its activity, and waits for a timeslot equal to NAV (the time required for the communicating nodes to send the packet successfully) and records the detailed information about the active neighbour nodes. If the overheard signal is outside the transmission range, but lies within the interference range then the node defers access for an Extended Inter-Frame Spacing (EIFS). While overhearing neighbour's activity, if the intended source and the destination pairs are already recorded then only the time of arrival of the packet, NAV and the signal strength of the transmitted power are updated.

3.2.4. Algorithm for updating neighbour's activity

Over a period of time, the state of the network changes due to nodes leaving or joining the network or nodes dying due to limited battery life or due to node movement. So, it is crucial to update the activity of all the active neighbour nodes and closely monitor the transmission power of all the active neighbours, because the transmission power of a source or relay node is not only dependant on distance, but it's also dependant on the transmission power of the active neighbour nodes, so that the best optimal power is used to reduce or avoid hidden node issue. Thus, by updating the activity of the neighbourhood and by observing their transmission powers, a source or relay node can use the fresh optimal transmission power and avoid using unnecessary higher transmission power when neighbourhood using higher transmission power is no longer active. During updating the active neighbour table, any records with a timestamp older than T seconds from the current time are removed from the list as shown in Table 3. In this paper, table updating time is considered as 1 s (due to consideration of highly mobile nodes), this is done in order to maintain the freshness of the network condition and remove inactive entries.

3.3. Contention aware backoff mechanism

The access mechanism follows IEEE 802.11 standard which uses CSMA/CA technique during channel contention. However, instead of using same set of initial backoff ranges, the study uses the backoff mechanism described in [3] where the initial backoff values are controlled dynamically based on the number of active neighbour nodes. In order to reduce the probability of collision during retransmission the backoff values are exponentially increased with reference to the assigned initial backoff ranges. Only three levels of contention i.e. LOW ($C_{level} = 0$), MODERATE ($C_{level} = 1$) and HIGH ($C_{level} = 2$) are taken into account. The level of contention $C_{level} = 0$, if no other active neighbour nodes are detected, $C_{level} = 1$ when

Table 1

Algorithm for adjusting transmission power.

```

When node  $i$  sends to node  $j$ 
IF  $Pkt_{type} = Routing$  THEN
    SET  $Tx\_Power_i$  to  $Power_{Max}$ 
ELSE IF  $Pkt_{type} = RTS/CTS$  THEN
    IF  $Entry_{OutCount} = 0$  THEN
        IF  $Entry_{InCount} = 0$  THEN
            SET  $Table_{Out}.ID$  to  $Dst_i$ 
            SET  $Table_{Out}.EstPt$  to  $Power_{Max}$ 
            SET  $Tx\_Power_i$  to  $Table_{Out}.EstPt$ 
            INCREMENT  $Entry_{OutCount}$ 
        ELSE
            FOR each row in the table  $Table_{In}$  until  $Entry_{InCount}$ 
                IF  $Table_{In}.ID = Dst_i$  THEN
                    SET  $Table_{Out}.ID$  to  $Dst_i$ 
                    SET  $Table_{Out}.EstPt$  to  $Table_{In}.EstPt$ 
                    SET  $Tx\_Power_i$  to  $Table_{Out}.EstPt$ 
                    INCREMENT  $Entry_{OutCount}$ 
                    BREAK
                ELSE
                    CONTINUE
            END IF
            SET  $RTS\_CTS_{TxPower}$  to  $Transmission\_Power_i$ ;
            SET  $Pt\_to\_RTS\_CTS_{TxPower}$ 
            END LOOP
        END IF
    ELSE
        FOR each row in the table  $Table_{Out}$  until  $Entry_{OutCount}$ 
            IF  $Table_{Out}.ID = Dst_i$  THEN
                FOR each row in the table  $Entry_{InCount}$ 
                    IF  $Table_{In}.ID = Dst_i$  THEN
                        SET  $Table_{Out}.EstPt$  to  $Table_{In}.EstPt$ 
                        BREAK
                    ELSE IF  $row + 1 = Entry_{InCount}$ 
                        SET  $Table_{Out}.EstPt$  to  $Power_{Max}$ 
                        BREAK
                    ELSE
                        CONTINUE
                END IF
            END LOOP
            IF  $Table_{Out}.EstPt < Overheard\_MaxPt$  THEN
                SET  $RTS\_CTS_{TxPower}$  to  $Overheard\_MaxPt$ 
                SET  $Tx\_Power_i$  to  $RTS\_CTS_{TxPower}$ 
            ELSE
                SET  $RTS\_CTS_{TxPower}$  to  $Table_{Out}.EstPt$ 
                SET  $Tx\_Power_i$  to  $RTS\_CTS_{TxPower}$ 
            BREAK
        END IF
        ELSE IF  $row + 1 = Entry_{OutCount}$ 
            SET  $Table_{Out}.ID$  to  $Dst_i$ 
            FOR each row in the table  $Table_{In}$  until  $Entry_{OutCount}$ 
                IF  $Table_{In}.ID = Dst_i$ 
                    SET  $Table_{Out}.EstPt$  to  $Table_{In}.EstPt$ 
                    SET  $RTS\_CTS_{TxPower}$  to  $Table_{Out}.EstPt$ 
                    SET  $Tx\_Power_i$  to  $RTS\_CTS_{TxPower}$ 
                    BREAK
            ELSE IF  $row + 1 = Entry_{InCount}$  THEN
                SET  $Table_{Out}.EstPt$  to  $Power_{Max}$ 
                SET  $RTS\_CTS_{TxPower}$  to  $Table_{Out}.EstPt$ 
                SET  $Tx\_Power_i$  to  $RTS\_CTS_{TxPower}$ 
            ELSE
                CONTINUE
            INCREMENT  $Entry_{OutCount}$ 
            BREAK
        ELSE
            CONTINUE
        END IF
    END LOOP
    END IF
    ELSE // Data or Ack
        FOR each row in the table  $Table_{Out}$  until  $Entry_{OutCount}$ 
            IF  $Table_{Out}.ID = Dst_i$  THEN
                IF  $Table_{Out}.EstPt < Overheard\_MaxPt$  THEN
                    SET  $Tx\_Power_i$  to  $Overheard\_MaxPt$ 
                ELSE
                    SET  $Tx\_Power_i$  to  $Table_{Out}.EstPt$ 
                BREAK
            END IF
        ELSE
            CONTINUE
        END IF
    END LOOP
    END IF

```

Table 2
Algorithm for recording neighbour's transmission power.

```

When node  $i$  overheard packet/frame from node  $j$ 
IF  $Power_{recv} \geq RX_{thresh\_}$  &&  $Dst_j \neq ID_i$  &&  $Pkt_{type} = RTS/CTS$  THEN
  IF  $Overheard_{rts\_cts} = 0$  THEN
    SET  $Table_{Overheard\_ID}$  to  $ID_j$ 
    SET  $Table_{Overheard\_Count}$  to 1
    INCREMENT  $Overheard_{rts\_cts}$ 
  ELSE
    FOR each count overheard rts/cts until  $Overheard_{rts\_cts}$ 
      IF  $Table_{Overheard\_ID} = ID_j$  THEN
        INCREMENT  $Table_{Overheard}[t].Count$ 
        IF  $Table_{Overheard\_Count} > 1$  THEN
          IF  $Count_{Neigh_i} = 0$  THEN

            SET  $Active_i^{Neighbour}$  to {  $ID_j, Dst_j, Time_j,$  }
               $NAV_j, Overheard\_Pt_j$ 
            INCREMENT  $Count\_Neigh_i$ 
          ELSE
            FOR each count neighbour until  $Count\_Neigh_i$ 
              IF  $Active_i^{Neighbour\_ID} = ID_j$  &&
                 $Active_i^{Neighbour\_Dst} = Dst_j$  THEN

                SET  $Active_i^{Neighbour}$  to {  $Time_j,$  }
                   $NAV_j, Overheard\_Pt_j$ 
              BREAK
            ELSE IF count neighbour +1 =  $Count\_Neigh_i$  THEN

              SET  $Active_i^{Neighbour}$  to {  $ID_j, Dst_j, Time_j,$  }
                 $NAV_j, Overheard\_Pt_j$ 
              INCREMENT  $Count\_Neigh_i$ 
              BREAK
            ELSE
              CONTINUE
            END IF
          END LOOP
        END IF
      ELSE
        IF count overheard rts/cts + 1 =  $Overheard_{rts\_cts}$  THEN
          SET  $Table_{Overheard\_ID}$  to  $ID_j$ 
          SET  $Table_{Overheard\_Count}$  to 1
          INCREMENT  $Overheard_{rts\_cts}$ 
          BREAK
        ELSE
          CONTINUE
        END IF
      END IF
    END LOOP
  END IF
ELSE
  IF count overheard rts/cts + 1 =  $Overheard_{rts\_cts}$  THEN
    SET  $Table_{Overheard\_ID}$  to  $ID_j$ 
    SET  $Table_{Overheard\_Count}$  to 1
    INCREMENT  $Overheard_{rts\_cts}$ 
    BREAK
  ELSE
    CONTINUE
  END IF
END IF
END LOOP
END IF

```

Table 3
Algorithm for updating neighbour's activity.

```

SET  $Temp\_Count$  to 0
FOR each count neighbour until  $Count\_Neigh_i$ 
  IF  $Active_i^{Neighbour\_Time} + Interval \geq Current\_Time$  THEN

    SET  $Temp_{Active_i}^{Neighbour}$  {  $ID_j, Dst_j, Time_j,$  } to
       $NAV_j, Overheard_{Pt_j}$ 

     $Active_i^{Neighbour}$  {  $ID_j, Dst_j, Time_j,$  }
       $NAV_j, Overheard_{Pt_j}$ 
    INCREMENT  $Temp\_Count$ 
  END IF
IF count + 1 =  $Count\_Neigh_i$  THEN
  FOR each count until  $Temp\_Count$ 

    SET  $Active_i^{Neighbour}$  {  $ID_j, Dst_j, Time_j,$  } to
       $NAV_j, Overheard_{Pt_j}$ 

     $Temp_{Active_i}^{Neighbour}$  {  $ID_j, Dst_j, Time_j,$  }
       $NAV_j, Overheard_{Pt_j}$ 
    SET  $Count\_Neigh_i$  to  $Temp\_Count$ 
  END IF
END LOOP

```

there are up to two other active neighbours within the transmission range, and $C_{level} = 2$, if there are at least three active nodes within the transmission range. Any retransmitted frame (r) is allowed to attempt up to seven times to deliver to the next hope and discard the frame otherwise. A frame is considered to be fresh if $r = 0$ and retransmitted if $r \geq 1$. The method of generation of back-off ranges depending on the number of active neighbourhood is shown in (3). The previous study conducted in [3] has analysed the gain in network performance in using such backoff mechanism, but failed to address the amount of energy used in adopting such back-off mechanism. So, this paper uses the same backoff mechanism to study the amount of energy consumed while using such mechanism during channel contention and deferring channel access.

$$CW_{C_{level}, r} = \begin{cases} 2^{(3+C_{level})} - 1; & r = 0 \\ 2^{(3+C_{level}+r)} - 1; & r \geq 1 \end{cases} \quad (3)$$

Where:

$$C_{level} = \{LOW = 0, MODERATE = 1, HIGH = 2\}$$

$$r = \{0, 1, 2, \dots, 7\}$$

4. Evaluation and discussion

The proposed dynamic power-controlled cross layer MAC is tested in considering different network scenarios and benchmarked against the following protocols:

- 1 IEEE802.11b: A standard MAC which uses a fixed maximum power ($Power_{Max}$) of transmission between the source and the next hop destination.
- 2 MaxRC-MinDA NA-PMAC: A variant of the proposed power-controlled MAC protocol where the RTS and the CTS packets are always transmitted using a maximum power ($Power_{Max}$). The Data packets as well as the ACK are sent using the estimated minimum transmission power (Est_{Pt}).
- 3 Min NA - PMAC: This also another variant of the proposed power-controlled MAC where any two communicating nodes transmits using only a minimum required transmission power between the two communicating nodes.

This paper thoroughly investigated the energy utilization of the active nodes against the distance of communication between the source and destination pair. The fairness issue is also addressed and analysed when multiple flows using multiple sources are considered. The effectiveness of the protocol is tested by considering random topologies with different traffic types namely CBR, TCP and Exponential in both the single hop as well as multi-hop scenarios. The study is conducted extensively and tested in both a static network as well as a dynamic network by considering high node mobility scenarios. All simulations were carried out with NS2, version 2.35 with the network parameters listed in Table 4 and an antenna parameters such as Transmitter Gain (G_t), Receiver Gain (G_r), Height of Transmitter (h_t), Height of receiver (h_r), Frequency (f), wavelength (λ) of the corresponding frequency, System Loss (L) are considered. The values of the antenna parameters of G_t , G_r , h_t , h_r , f and L are 1.0 dBd, 1.0 dBd, 1.5 m, 1.5 m, 914.06 Hz and 1.0 respectively. Duration of each round of simulation lasts 1000 seconds and resultant value is an average of 100 rounds of simulations for all the cases.

4.1. Analysis of energy usage over distance

Since, Min NA-PMAC, MaxRC-MinDA NA-PMAC, and Dynamic NA -PMAC are power control communication mechanisms, when the communicating nodes are closer, the amount of energy usage is less compared to the situation when the communicating nodes are at a greater distance. As the distance between the communicating nodes increases the energy utilization is expected to increase

Table 4
Network simulation setup.

Parameter	Value/protocol used
Grid Size	500 m ² /1000 m ²
Routing Protocol	AODV
Queue Type	DropTail
Queue Size	100
Bandwidth	2 Mbps
SIFS	10 μ s
DIFS	50 μ s
Length of Slot	20 μ s
Default Power (P_t)	24.49 dBm
Default $RXThresh$	-64.37 dBm
Default $CSThresh$	-78.07 dBm
$CPThresh$	10.0
Max_{Retry}	7
Simulation Time	1000 second
Traffic Type	CBR/TCP/Exponential
Frame size	1000 bytes
Speed	0 m/s, 20 m/s and 40 m/s

rapidly. Here, the study is conducted to measure the energy usage during transmission and the amount of remaining energy level when two communicating nodes i as source and node j as destination are considered with an increasing distance of communication between them from 20 m to 250 m. During the test, some additional network parameters are considered in addition to the network parameters listed in Table 4. If the node is in a sleep mode then the amount of power consumed in a second is 0.001 W, when a node goes to an idle state from a sleep state it requires 0.2 W of power and the time required to wake up is 0.005 s. Initially each node is charged with 1000 Joules of energy and simulation is carried out for 1000 s. The transmission powers of an active node for Min NA-PMAC, MaxRC-MinDA NA-PMAC and Dynamic NA-PMAC power-controlled protocol are estimated as per the distance between the source and the destination node. The energy utilization of actively engaged nodes is studied in detail in the next subsections.

4.1.1. Energy utilization during deferring/contention at the source

When the node defers accessing the channel, the node is considered to be in an idle mode. In such an idle mode, during the simulation of 1000 s and the communicating distance of 20 m, the amount of energy used while deferring is 67.40 J, 25.71 J, 25.69 J, and 25.67 J for IEEE 802.11b, MaxRC-MinDA NA-PMAC, Min NA-PMAC, and Dynamic NA-PMAC protocols respectively. Thus the gain of energy because of using the new neighbour aware backoff mechanism is 62% compared to the deferring technique used in IEEE 802.11b when two nodes are active. Irrespective of the distance of communication with next hop pair, the amount of energy gain while deferring using the new technique against the standard IEEE 802.11b deferring technique is approximately 62%. Thus, the power-controlled MaxRC-MinDA NA-PMAC, Min NA-PMAC, and Dynamic NA-PMAC medium access control protocols uses very less energy while deferring, it is due to the fact that when the number of active nodes are low, a small backoff values are chosen (so less deferring time), unlike the IEEE802.11b where a fixed range of backoff values are considered irrespective of the degree of contention.

4.1.2. Total remaining energy at the source

The amount of energy used by a source node over an increasing distance of communication is shown in Fig. 6. The total amount of energy spent by the source node when it conducts sensing, sending of RTS and Data frames, reception of CTS and ACK, sending/reception of any other frames like routing frames and energy spent during deferring or backoff is highlighted in Fig. 6. On the

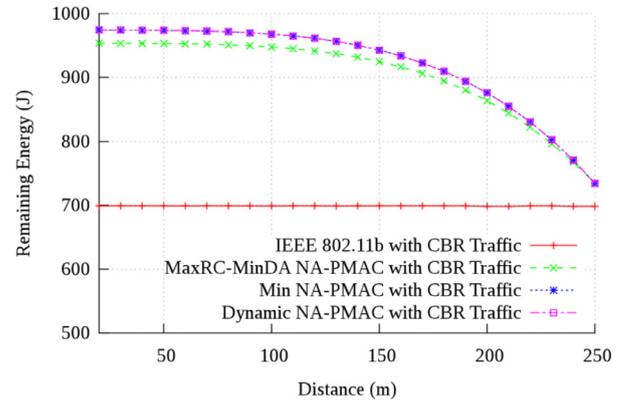


Fig. 6. Total remaining energy of the source.

other hand, it also shows the amount of remaining energy in a node when the communicating distance between the source and the destination increases. When a fixed transmission power mechanism using IEEE 802.11b is deployed, the source node consumed approximately 30% of the battery life irrespective of the distance of communication with the next hop when the node was active for 1 K seconds. Among the three power-controlled mechanisms, MaxRC-MinDA NA-PMAC the overall power consumption when the distance of communication is short is much higher to that of the power-controlled MAC protocols Min NA-PMAC, and Dynamic NA-PMAC, because in such protocol the RTS and the CTS control frames are sent with highest transmission power. When the distance of communication is 20 m, there is an energy gain of approximately 44% over MaxRC-MinDA NA-PMAC when Min NA-PMAC and Dynamic NA-PMAC is used. Even when the distance of communication converges towards the maximum transmission power to cover 250 m, the overall power consumption of the power-controlled mechanisms is only 26.5% compared to the fixed transmission power like IEEE 802.11b which uses 30% of the total battery life. This effect is due to the new backoff mechanism where a small backoff value is chosen when the number of active neighbours is low.

4.1.3. Energy utilization during deferring/contention at the destination

When the distance of communication between the source and the destination is only 20 m, the amount of energy used while deferring is 67.40 J when IEEE 802.11b MAC protocol is considered. In the similar scenario, the amount of energy used while deferring in MaxRC-MinDA NA-PMAC, Min NA-PMAC and Dynamic NA-PMAC protocols are 25.71 J, 25.70 J, and 25.68 J respectively. In fact, irrespective of the distance of communication MaxRC-MinDA NA-PMAC, Min NA-PMAC and Dynamic NA-PMAC saves approximately 61% of the energy compared with the energy used by IEEE 802.11b during contention, because smaller backoff values are considered by the proposed backoff mechanism when the numbers of active neighbours are few. Moreover, the amount of energy saved during deferring as a source node or a destination node is similar.

4.1.4. Total remaining energy at destination

The amount of energy used by a destination node over an increasing distance of communication is shown in Fig. 6. Activities of the destination node is limited compared to the source node, because it response to the source node with a small control frames like CTS and ACK, so the energy usage is expected to be less compared to the source which generates Data. Fig. 7 reflects both the amount of energy used as well as the total amount of remaining energy of an active destination node from the given initial energy when the communication takes place for duration of 1000 seconds.

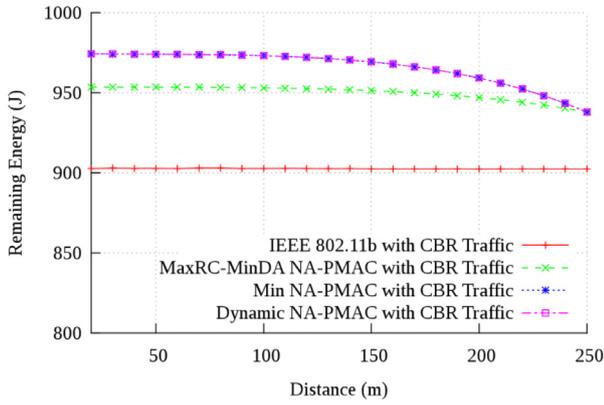


Fig. 7. Remaining energy at destination.

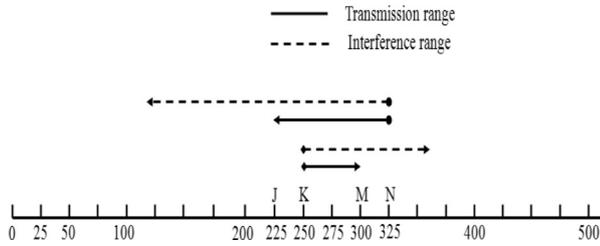


Fig. 8. Partial hidden node issue.

When a fixed transmission power like IEEE 802.11b is used, a total energy of approximately 10% (total remaining energy is 90%) is consumed irrespective of the distance of communication between the source and the next hop destination. In the similar scenario, the amount of the energy used in case of MaxRC-MinDA NA-PMAC, Min NA-PMAC and Dynamic NA -PMAC varies. When the distance of communication is short (say 20 m), the total amount of energy used is approximately 5% (total remaining energy is 95%) when MaxRC-MinDA NA-PMAC is used, while Min NA-PMAC and Dynamic NA -PMAC used only 2.5% (total remaining energy is 97.5%) of the total initial energy. As the distance of communication increases, the amount of energy used in power-controlled MACs also increases, however it does not used as much as the energy consumed by IEEE 802.11b despite conversing to a maximum transmission power as shown in Fig. 8, because of adopting a dynamic backoff mechanism based on the number of active neighbours.

4.2. Partially hidden node fairness issue

When the transmission power is controlled, node i may communicate with node j using a transmission power P_{ij} and a neighbour node k may communicate with another node l with a power P_{kl} , where $P_{ij} >> P_{kl}$; in such situation the node sending with higher power may interfere other nodes communicating with lower power, but may not be aware about their existence since they communicate with low transmission power. Fig. 8, depicts such a partially hidden node issue, where two different pairs of communicating nodes are considered; node K sends Data to node M and node N sends Data to node J. So, when power is controlled, and if neighbours activity is ignored then node K sends to node M with a power to cover the distance of 51 m. When node N sends to node J, then the transmission power is estimated to cover 101 m. Thus, the generation of RTS and Data packets from node N and CTS and ACK from node J are overheard by both the nodes K and M, but unfortunately the RTS and Data generated by node K is not heard by node N since it is out of the transmission range when the power is controlled based on $d + \Delta$ communication range, but

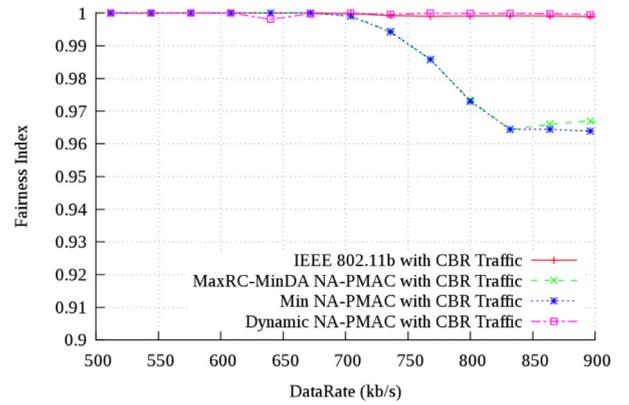


Fig. 9. Fairness index of partial hidden node issue.

activity of node K interferes the activity of node N. Likewise, the CTS and ACK generated by node M for node K are not within the transmission range of node J, but interferes the activity of node J. Since, RTS and CTS are used; node K and M can listen to all the activity of node J and N, but as discussed the activity of node K and node M are hidden to node N and node J respectively. In order to make the activity of node K and node M heard by node N and J respectively, node K estimates a new optimal transmission power i.e. $Overheard_Max_{P_t}$ to cover the furthest active neighbour node (1 to n) from the source node i , $Max_i^1 \text{ to } n \{P_{i \rightarrow 1}, P_{i \rightarrow 2}, \dots, P_{i \rightarrow n}\}$, where $P_{i \rightarrow 1}$ is the power to reach node 1 from an active node i .

$$J(x_1, x_2, x_3, \dots, x_n) = \frac{(\sum_{i=1}^n x_i)^2}{n \cdot \sum_{i=1}^n x_i^2} \quad (4)$$

As shown in Fig. 9, as the offered load in the network increases and the network gets saturated, the fairness of the competing flows of network topology shown in Fig. 8 is better in Dynamic NA -PMAC performs compared to that of MaxRC-MinDA NA-PMAC and Min NA-PMAC power-controlled MACs. It is due to the fact that the transmission power of node K and M are re-adjusted to reach node N and J respectively. The fairness index of IEEE 802.11b is expected to be fair due to transmission using a maximum power. The fairness index is measured using (4) Jain's fairness index [28]. In Dynamic NA -PMAC and IEEE 802.11b, the degree of fairness is 99.99% and 99.90% respectively during a saturated network region, which is an ideal state of fairness. However, when the network is saturated and uses MaxRC-MinDA NA-PMAC and Min NA-PMAC power-controlled MAC, the fairness of the flows is affected because of the hidden node issue and restricts the fairness to 96.50%. The overall network throughput of the power-controlled MACs are compatible with a fixed transmission power IEEE 802.11b even when the network is saturated.

4.3. Random topology

This is the section where the main test is conducted to validate and verified the robustness of the designed protocols. The proposed powered control MAC Dynamic NA -PMAC is tested against other power-controlled MAC techniques such as MaxRC-MinDA NA-PMAC and Min NA-PMAC and benchmarked the performance with a fixed transmission power IEEE 802.11b. Initially, a test is conducted to explore the probability of concurrent transmission when transmission power is controlled using a single hop communication with random node deployment as shown in Fig. 10, using the network parameters listed in Table 4 with a defined space boundary. The random topology for concurrency test is carried out using different kind of traffic like CBR, TCP, and Exponential. The detail study of the topology arrangement and the network perfor-

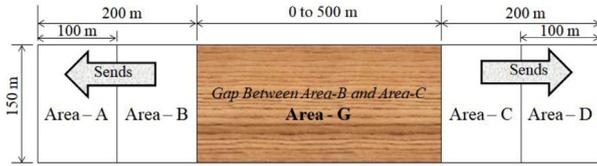


Fig. 10. Random topology for single hop with fixed boundaries.

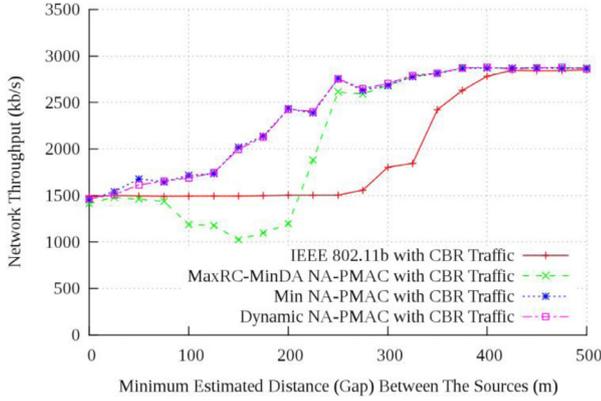


Fig. 11. Network performance of random sources and destinations using real time traffic (CBR).

mance are explained in Section 4.3.1. After successfully conducting the concurrency test using a single hop without node mobility, the Section 4.3.2 conducts an elaborate study of the network performance in terms of throughput and the average energy usage in a random topology with node mobility consideration in a multi-hop environment as shown in Fig. 14 and Fig. 15 with multi-hop scenarios by taking node mobility in account. In all the study, same packet sizes of 1000 bytes and a per flow data rate of 2000 kb/s is considered in case of CBR and Exponential traffic.

4.3.1. Random topology for testing concurrent transmission with static networks

As per the topology space arrangement of Fig. 10, the network is divided into four: 150 m x 100 m sections with same areal space called Area-A, Area-B, Area-C, and Area-D, with each section containing 10 nodes which are deployed randomly. The fifth areal section called Area-G is considered with its areal length varied from (0 m to 500 m) x 150 m. This is the space of separation between the areal section of Area-B and Area-C from where the random sources are picked. Destination nodes are selected randomly, from Area-A and Area-D for the random sources which are randomly picked from Area-B and Area-C respectively. The space divided in Fig. 10 allows any node deployed in section Area-B communicate with nodes of section Area-A and any nodes deployed in section Area-C can reach any nodes of section Area-D with a one hop communication using a maximum transmission range. The Area-G which separates the areal sections Area-B and Area-C is increased by a factor of 25 m and analysed the overall network performance using a UDP connection with CBR application, TCP traffic, and exponential traffic. In exponential traffic generation, the burst time (the time when the Data is generated continuously) and the idle time (the time when the source goes silent) are both considered to be the same in this paper with a value of 0.5 s.

4.3.1.1. Random topology with CBR traffic. Fig. 11 shows the network performance of a network topology setup shown in Fig. 10, with the help of the network parameters listed in Table 4, exhibiting concurrent transmission in power control mechanisms. As the distance of separation between the sources of areal sections B and C

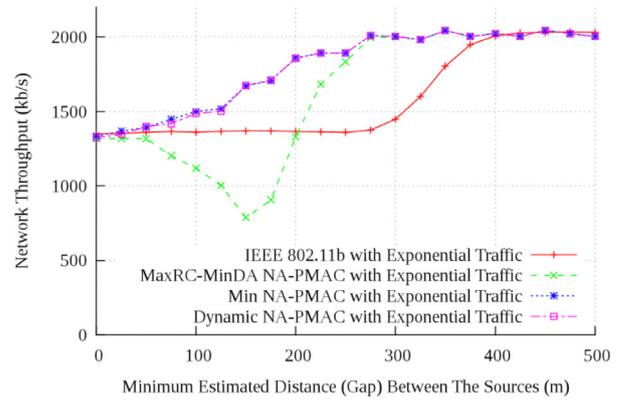


Fig. 12. Network performance of random sources and destinations using exponential traffic.

increases, the total network performance of the proposed protocol Dynamic NA -PMAC and its variant Min NA-PMAC increases eventually. However, due to the use of maximum transmission power for RTS and CTS in MaxRC-MinDA NA-PMAC, the performance of the network is not improved until the minimum separation between the sources is at least 200 m. Moreover, due to the use of maximum transmission range for Data and ACK, the performance of the MaxRC-MinDA NA-PMAC drops as low as 33% compared to IEEE 802.11b when Dynamic NA -PMAC and Min NA-PMAC increases its network performance due to early concurrent transmission as shown in Fig. 10. In both Dynamic NA -PMAC and Min NA-PMAC, the performance of the overall network increases as the distance of separation between the sources increases because, the probability of concurrent transmission increases, unlike MaxRC-MinDA NA-PMAC which is late start. In case of an IEEE 802.11b, the probability of parallel transmission of the sources is possible only when the areal separation between the sources is at least 275 m. As the areal distance of separation between the sources increases, the probability of parallel communication increases tremendously for Dynamic NA -PMAC and Min NA-PMAC from the situation when the distance of separation of Area-G is only 25 m. When the length of Area-G is 200 m, MaxRC-MinDA NA-PMAC power-controlled MAC performs 20% less than the fixed transmission power IEEE 802.11b, however, Dynamic NA -PMAC and Min NA-PMAC performs 63% better than IEEE 802.11b.

4.3.1.2. Random topology with exponential traffic. The random network topology setup of Fig. 10 is considered for evaluating the performance of exponential traffic using the power-controlled MACs and the IEEE802.11b. In terms of overall network performance, generating a CBR traffic gains higher end-to-end throughput compared to exponential traffic. This is due to the fact that, Data is generated at a constant rate throughout the duration of the communication, unlike exponential traffic where the source generates traffic only during burst time. In this paper, the burst time and the idle time are considered to be equal and the source burst Data for 0.5 seconds. As shown in Fig. 12, Min NA-PMAC and Dynamic NA -PMAC power-controlled MAC performs with higher throughput as the minimum distance between the sources increases unlike MaxRC-MinDA NA-PMAC and IEEE 802.11b MAC. The negative impact of sending RTS and CTS using maximum transmission power in MaxRC-MinDA NA-PMAC is seen in Fig. 14. Parallel communication is feasible only after the distance between the sources is approximately 200 m in MaxRC-MinDA NA-PMAC. When the areal distance of Area-G is 200 m apart, the performance of IEEE 802.11b and MaxRC-MinDA NA-PMAC are similar, but the performance of Min NA-PMAC and Dynamic NA -PMAC is very high and gains at

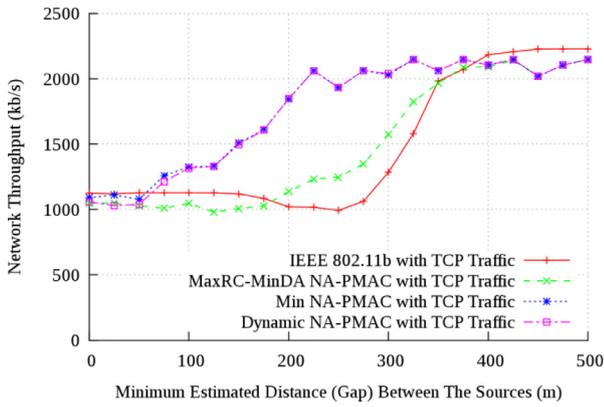


Fig. 13. Network performance of random sources and destinations using TCP traffic.

least 35% compared to IEEE 802.11b and MaxRC-MinDA NA-PMAC. In case of IEEE 802.11b MAC, the probability of parallel transmission is viable only when the length of the areal gap of separation between the sources is 275 m or greater.

4.3.1.3. *Random topology with TCP traffic.* Lastly, the random topology of Fig. 10 is tested with TCP traffic and the network performance of the power-controlled MACs and the IEEE 802.11b is shown in Fig. 13. It is to test the probability of concurrent data transmission when transmission power is controlled. The gain of network performance in terms of concurrent transmission occurs only after the minimum distance between the sources is 50 m. The exhibition of concurrent transmission is more vivid in Min NA-PMAC and Dynamic NA-PMAC compared to the MaxRC-MinDA NA-PMAC, which uses a maximum transmission power for RTS and CTS frames. In case of a power-controlled MAC Min NA-PMAC and Dynamic NA-PMAC the performance gain is over 80% and 63% compared to IEEE 802.11b and MaxRC-MinDA NA-PMAC respectively when the distance of communication among the sources are 200 m apart. However, a fixed transmission power IEEE 802.11b performs better when TCP traffic is generated when the communicating nodes are out of the interference range of each other.

4.3.2. *Random topology with Multi-hop communication in dynamic networks*

In this part of the study, the network deployment area is divided into two categories of different sizes i.e. Small (500 m²) and Large (1000 m²). However, the number of random nodes deployed in both the areas is the same with 100 nodes each, so that the node deployment is congested in a smaller deployment space and sparser in the larger area as shown as a snapshot of a sample node deployment in Fig. 14 and Fig. 15 respectively. The nodes are deployed in random with a random selection of sources and destination pairs. Initially, the performance of the network is studied without taking node mobility into account and later, source and destination pairs are allowed to move randomly with a constant speed of 20 m/s and 40 m/s. The performance of the network is evaluated in both the deployment spaces using fewer source and destination pairs (i.e. three) and a larger source and destination pairs (i.e. ten). Since the sources and the destinations are selected in random over a deployment space of 500 m² and 1000 m², the chances of delivering data in a multi-hop communication is certain. The available shared bandwidth within the neighbourhood is saturated by injecting high per flow data rate of 2000 kb/s with a large packet size of 1000 bytes and saturate the limited shared bandwidth in all the scenarios.

The average performance of the network is calculated using $\sum_{i=1}^F T_i/S_t$, where T_i is the throughput of i^{th} flow in kb, F is the

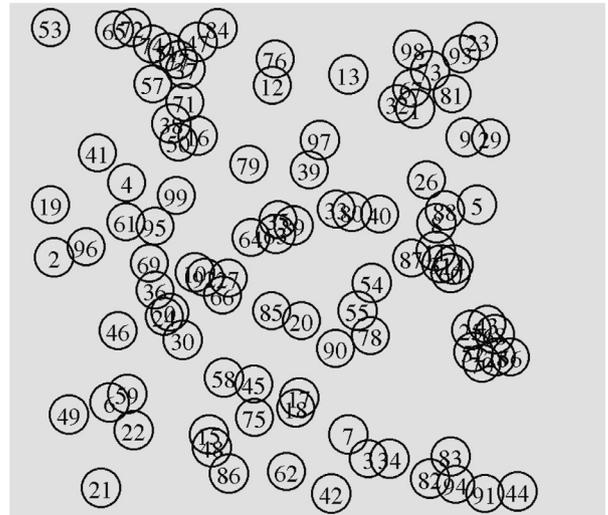


Fig. 14. Deployment of 100 nodes in 500 m².

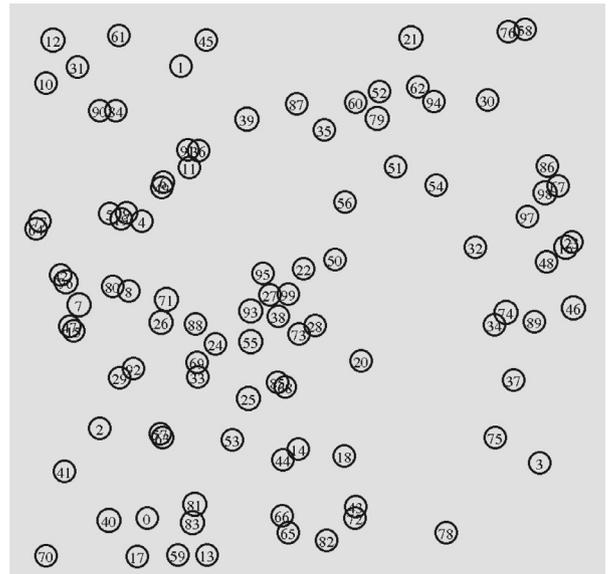


Fig. 15. Deployment of 100 nodes in 1000 m².

total number of flows and S_t is the simulation time in second. During the evaluation of the energy usage of the active nodes, the energy utilization of all the nodes in the network is taken into account and an average energy is calculated because in Ad-hoc networks, it's not only the source or the destinations that usage energy, but all the active (source, destination, relay) as well as the passive nodes (neighbours) usages energy. The average energy usage of a node/second is calculated using $(\sum_{j=1}^N E_j/S_t)/N$, where E_j is

the energy used by j^{th} node in mJ during a simulation time of S_t and N is the total number nodes in the network. The simulation is conducted by considering both light and heavy traffic loads of 6%–20% of the deployed nodes as source/destination in both the small (500 m²) and large (1000 m²) deployment spaces.

4.3.2.1. *Network performance in small deployment space i.e. 500 m².* The performance graph of Fig. 16 is for a densely populated network with fewer source and destination pair. When a bandwidth is shared and is limited, increasing the number of flows will not lead to higher network performance in a saturated network condition. When the number of actively participating nodes in delivering

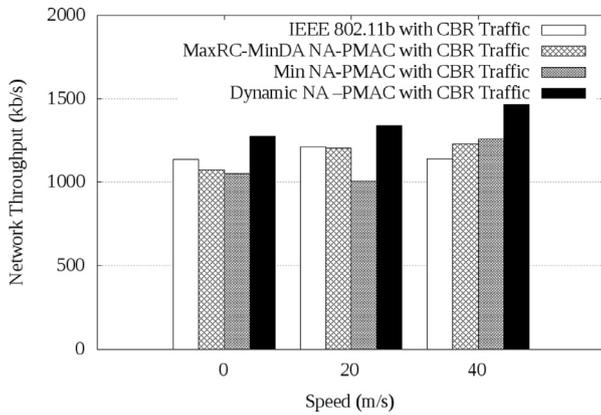


Fig. 16. Network performance in 500 m² with fewer source and destination pairs (i.e. three pairs).

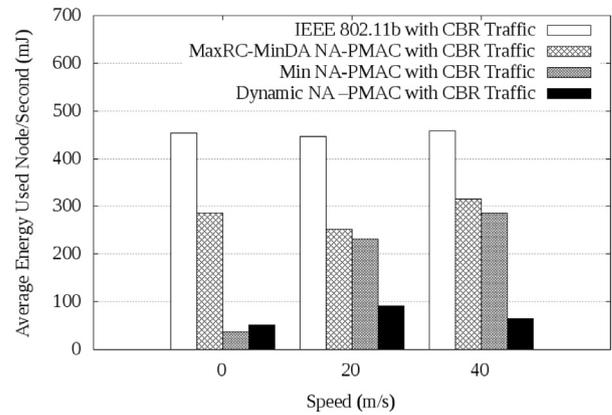


Fig. 18. Battery utilization in 500 m² with fewer source and destination pairs (i.e. three pairs).

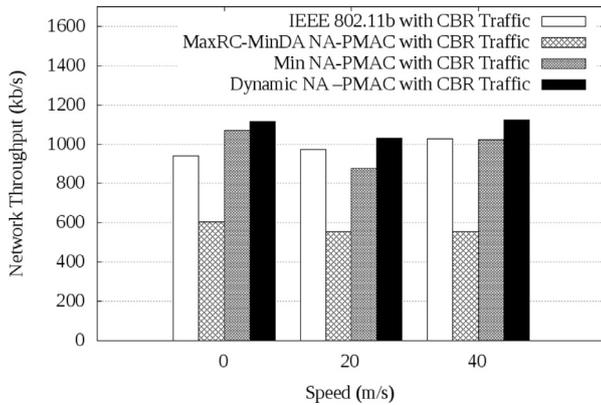


Fig. 17. Network performance in 500 m² with large source and destination pairs (i.e. ten pairs).

frames from the source to destination nodes are fewer, the overall network performance improves with the speed of the movement of the source and destination nodes because higher chances of concurrent transmission is introduced in Dynamic NA-PMAC and dealt hidden node issues better compared to a fixed IEEE 802.11b power control mechanism. In fact, the performance of the Dynamic NA-PMAC outperforms other power-controlled mechanisms like MaxRC-MinDA NA-PMAC and Min NA-PMAC as well, because of transmitting the control RTS and CTS frames using a maximum transmission leading to higher interfering space and leading to higher hidden node situations for using minimum transmission power. Whether the nodes are stationary or mobile, Dynamic NA-PMAC performs better compared to all the other power-controlled mechanisms like IEEE 802.11b, MaxRC-MinDA NA-PMAC and Min NA-PMAC. When the nodes are stationary Dynamic NA-PMAC gains at least 12% compared to a fixed power transmission system. When the node moves at a speed of 20 m/s to 40 m/s then the performance gains goes up from 10% to 28% in case of Dynamic NA-PMAC compared to fixed transmission power. In case of a transmission power MACs like MaxRC-MinDA NA-PMAC and Min NA-PMAC, the performance gain of Dynamic NA-PMAC ranges from 11%–19% and 16–33% respectively, depending on nodes being stationary or mobile.

The performance graph of Fig. 17 is for a densely populated network with high number of source and destination pair. In a saturated network environment, introducing more flows leads to lower overall network performance as shown in Fig. 17 where 20% of the deployed nodes are either source or destination compared to the situation where only 6% are either source or destination as shown

in Fig. 16, because of heavy loss due to congestion. In heavily active nodes, it is observed that performance gain by Dynamic NA-PMAC over a fixed transmission power when nodes are stationary and mobile with a speed ranging from 20 m/s to 40 m/s is approximately 18% and (5–10%) respectively. In comparison to MaxRC-MinDA NA-PMAC and Min NA-PMAC, Dynamic NA-PMAC gains a network performance of 84% and 5% respectively when nodes are stationary and when nodes are mobile with a high speed ranging from 20 m/s to 40 m/s the performance gain leads to (86–102%) and (10–17%) respectively. It is also observed that in a heavily active environment, MaxRC-MinDA NA-PMAC power control mechanism performs worse than fixed transmission power control mechanism like that of IEEE 802.11b.

4.3.2.2. Battery usage in small deployment space i.e. 500 m². The graph of Fig. 18 depicts the battery utilization of a densely populated network with fewer source and destination pair. In an ideal network condition, generally a higher packet delivery rate leads to higher usage of energy when the data rate and bandwidth are fixed. However, in a real environment, the battery usage of each participating node is not directly proportional to the throughput of the network because the throughput may be affected by congestion, collision, hidden and exposed nodes. Thus, higher energy usage may not reflect a corresponding higher throughput, rather a protocol that can deal better with congestion or collision or hidden or exposed node issues may lead to higher throughput while using less energy. The aim of a power control is not only to save energy and increase concurrent transmission in a shared bandwidth environment, rather it should also be able to deal with the hidden/exposed issues to reduce frame collision and increase the overall network performance which is explicitly displayed by Dynamic NA-PMAC. Even if a min transmission power is adopted in Min NA-PMAC, the amount of average energy usage per node is relatively high when nodes are mobile, it is due to fact that higher degree of hidden nodes are introduced due to low transmission power which leads to lower throughput as shown in Fig. 16 and higher energy usage as shown in Fig. 18 except when nodes are stationary. It is expected that energy usage will be much higher for a fixed transmission power like IEEE 802.11b and MaxRC-MinDA NA-PMAC as depicted in Fig. 18. When nodes are moving at a high speed the energy usage is at least twice to that of Dynamic NA-PMAC in case of MaxRC-MinDA NA-PMAC and Min NA-PMAC. While the power usage of IEEE 802.11b is approximately four times the energy usage of Dynamic NA-PMAC whether in stationary or high-speed mobile node conditions.

The graph of Fig. 19 shows the battery utilization of a densely populated network with high number of source and destination

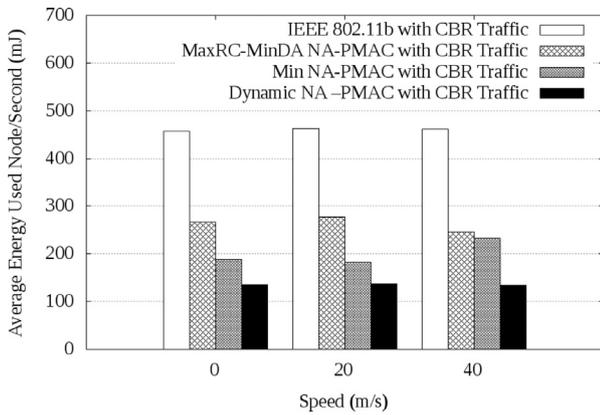


Fig. 19. Battery utilization in 500 m² with large source and destination pairs (i.e. ten pairs).

pair. The overall energy usage of Dynamic NA-PMAC is higher when the number of active node increases as shown in Fig. 19, however, the overall energy usage is much less compared to all the other fixed transmission power mechanism or a power-controlled mechanism like MaxRC-MinDA NA-PMAC and Min NA-PMAC. Transmission using a minimum power does not guarantee lesser energy usage in a distributed environment because it can lead to higher retransmission attempts due to collision and hidden node issues and lead to lower throughput and higher energy usage as shown in Fig. 19. However, when nodes are static and numbers of active nodes are fewer, energy usage can be lower as shown in Fig. 18 for a minimum power transmission due to decrease in number of successful transmission. Moreover, the overall energy usage of Min NA-PMAC is high compared to Dynamic NA-PMAC when nodes are static or mobile in comparison to Dynamic NA-PMAC when the number of active node increases. In case of transmission using different powers depending on frame types in MaxRC-MinDA NA-PMAC, the throughput is lowered, but uses higher energy because of reduction in concurrent transmission and increase in collision and hidden node issues. Even though the path lengths are same in all the considered power-controlled mechanisms, the network performance and energy usage is worst in a fixed transmission method due to high interference and sending all frames using maximum power.

4.3.2.3. Network performance in large deployment space i.e. 1000 m².

When the number of deployed nodes remains the same, but if the area of deployment is increased, the nodes are expected to be located more sparsely. Moreover, when the area of deployment is larger, the random selection of source and destination will eventually lead to a path length with a higher hop count compared to when the deployment area is smaller and eventually affect the overall network performance as discussed in [1]. It is evident as shown in Fig. 20 and Fig. 21 that when the area of deployment is increased from 500 m² to 1000 m², the overall network performance is decreased.

The graph of Fig. 20 represents the network performance of a sparsely populated network with fewer source and destination pair. As shown in Fig. 20, when the area of deployment is large, and nodes are sparsely located, fixed transmission power MAC 802.11b and Min NA-PMAC performs better to that of MaxRC-MinDA NA-PMAC and Dynamic NA-PMAC when nodes are static. When nodes don't move, using a minimum transmission power is more effective due to the fact that the numbers of active nodes are relatively less compared to the area of deployment and hidden nodes are relatively reduced as space increases. On the other hand using a maximum transmission power also reduces hidden

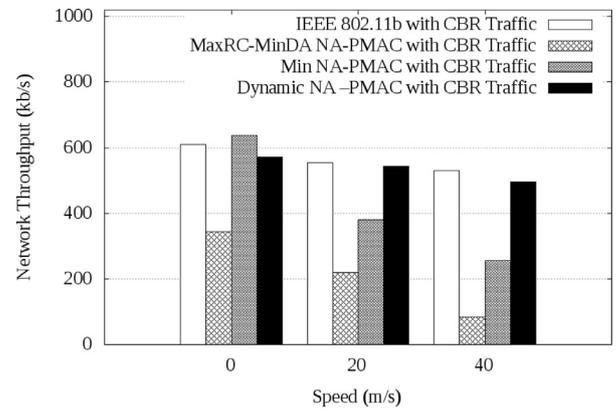


Fig. 20. Network performance in 1000 m² with fewer source and destination pairs (i.e. three pairs).

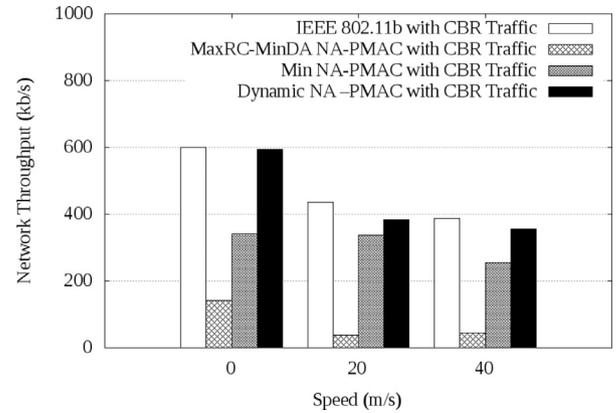


Fig. 21. Network performance in 1000 m² with large source and destination pairs (i.e. ten pairs).

node issues when the node per deployed area is larger. However, the network performance of MaxRC-MinDA NA-PMAC and Min NA-PMAC reduces as the source and destination nodes moves at higher speed as shown in Fig. 20. Irrespective of the nodes status (static or mobile), MaxRC-MinDA NA-PMAC does not perform well and the performance worsen as the speed of the nodes increases. When the speed of source/destination moves with 40 m/s, Dynamic NA-PMAC performs approximately twice that of Min NA-PMAC and over five times the performance of MaxRC-MinDA NA-PMAC. It is also observed that when node density over the deployment area is lesser, in terms of performance gain, maximum power model is compatible with Dynamic NA-PMAC, but the energy utilization of Dynamic NA-PMAC is far better to that of a maximum transmission power like IEEE 802.11b.

The graph of Fig. 21 represents the network performance of a sparsely populated network with higher number of source and destination pair. When node moves with higher speed, it is evident from Fig. 20 and Fig. 21 that increasing the number of flows in a network does not improve the overall network performance, rather it decreases. However, when nodes are static, then the performance of a maximum power transmission model performs better to that of power-controlled models. Unlike, the performance of Min NA-PMAC in a low density sources when nodes are static; min power model Min NA-PMAC degrades its performance when the numbers of active sources are increased. When the speed of the sources and the number of flows in the network increases, MaxRC-MinDA NA-PMAC finds it hard to survive unlike other power control model it is due to the uneven interfering it creates due to its varying power control based on frame type. So, controlling power in such manner is highly undesirable.

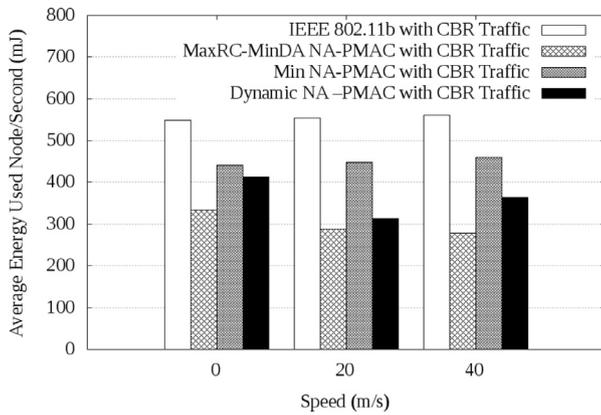


Fig. 22. Battery utilization in 1000 m² with fewer source and destination pairs (i.e. three pairs).

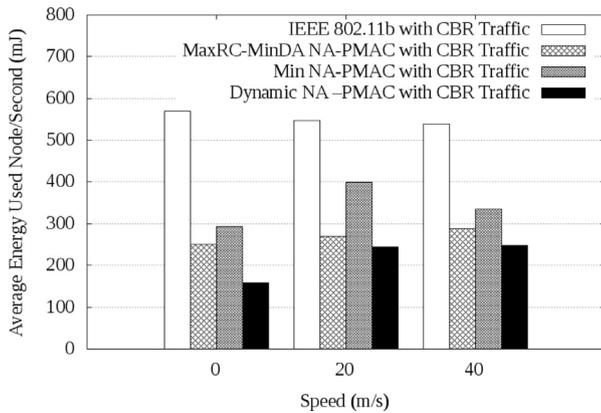


Fig. 23. Battery utilization in 1000 m² with large source and destination pairs (i.e. ten pairs).

4.3.2.4. *Battery usage in large deployment space i.e. 1000 m².* The graph of Fig. 22 represents the battery utilization of a sparsely populated network with fewer source and destination pair. In terms of network performance, whether the number of flows is few or many if the deployment area is large and the node density is less, the maximum power transmission model like IEEE 802.11b also performs well unlike when the node density is high. However, the energy utilization is very high compared to any other power-controlled models like MaxRC-MinDA NA-PMAC, Dynamic NA-PMAC, and Dynamic NA-PMAC as shown in Fig. 22. When the number of nodes as source/destination is only 6% and node status is either static or mobile, the amount of energy used across all the power control models and IEEE 802.11b are consistent. When nodes are static or mobile, it's interesting to observe that MaxRC-MinDA NA-PMAC uses lesser per node energy despite using a varying transmission power based on frame types, it is due to the fact that it could not deliver as many frames to destinations as other mechanism as shown in Fig. 20.

The graph of Fig. 23 depicts the battery utilization of a sparsely populated network with high number of source and destination pair. The average battery utilization of the nodes does not increased compared to when the number of source and destination pairs are lesser because the network is saturated and in fact, increasing the number of flows in such scenarios degrades the network performance as shown in Fig. 21 against Fig. 20. Moreover, the battery utilization shown in Fig. 23 indicates that when the success rate of frame delivery decreases the overall battery utilization of also decreases. During such environment when the numbers of flows are increased and node density is decreased by in-

creasing the deployment area as shown in Fig. 15, Dynamic NA-PMAC outperforms all the other power-controlled MAC and fixed maximum transmission power communication like IEEE 802.11b. Irrespective of the status of the nodes (static or mobile) the battery utilization is least in Dynamic NA-PMAC. It is also observed that communicating with minimum power does not lead to less energy utilization rather its all dependant on the successful frame delivery rate and other factors like frame collision, retransmission, deferring mechanism, hidden node issues etc.

5. Conclusion and future direction

This paper proposed a new power-controlled MAC called Dynamic Neighbour Aware Power-controlled MAC (Dynamic NA -PMAC) and benchmarked against variant of power control MAC like MaxRC-MinDA NA-PMAC (where RTS and CTS are sent with full power and Data and ACK are sent with minimum power) and Min NA-PMAC (uses minimum transmission power for all form of communication). Use of different transmission power for control frames and Data leads to lower probability of concurrent transmission when compared to a technique which uses a same transmission power for all types of frames. Moreover, such approach leads to lower performance when the distances between the sources are close. The degree of fairness can be enhanced by considering the neighbour's transmission power instead of using a minimum transmission power between a source and a next hop destination. The probability of parallel transmission of multiple sources in a random topology in the increasing order of efficiency is IEEE 802.11b, MaxRC-MinDA NA-PMAC, Min NA-PMAC and Dynamic NA -PMAC when node density is less. Moreover, when node density is high, and nodes are either stationary or mobile MaxRC-MinDA NA-PMAC is highly undesirable. In such scenario the performance of IEEE 802.11b is compatible with Dynamic NA -PMAC even though the energy usage of IEEE 802.11b can be threefold to that of Dynamic NA -PMAC. Thus, the network performance is dependent on the node density and the number of active nodes over a deployed area and when network is saturated increasing the deployment area does not have positive impact on the overall network performance rather it decreases due to higher hop path length. The backoff based on the number of active neighbours thus improve the energy utilization especially when the number of active neighbours is low. Despite high node mobility in a multi-hop environment, Dynamic NA -PMAC is resilient and achieve high concurrent transmission and enhance the network performance by upto 28% and enhances the durability of node's battery life because energy usage is as low as 1/9th to 1/5th compare to a maximum transmission model.

In controlling transmission power, the main issue is the development of hidden nodes; increasing the transmission power of an active node may lead to a lower hidden node issue but compromises with the interference level. On the other hand, decreasing a transmission power may lead to higher hidden node issue and lower throughput due to hop count. So, in future, it will be interesting to explore the impact and effect of hidden nodes against throughput and fairness when transmission power is controlled and explore the possibility to maintain an end-to-end QoS in a highly mobile network to achieve real time communication in such environment.

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