STDMA Scheduling for WLANs and WPANs with Non-Uniform Traffic Demand

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Abstract—**Directional antennas provide many advantages such as higher gain, increased capacity, increased range, and reduced interference by concentrating radio signal energy in one direction. To take advantage of the reduced interference, this paper proposes a concurrent transmission scheduling method for wireless personal or local area networks deployed with directional antennas. In typical network deployment scenarios, it is quite likely to have non-uniform node densities and traffic demands in various parts of the network. To handle such situations and provide load-based service to various parts of the network while aiming to maximize the spatial reuse, this paper proposes a zone-based concurrent data transmission scheduling method. Simulation results show that the proposed method can support a larger number of flows while satisfying a greater fraction of the traffic demands from highly loaded regions, compared to existing methods.**

I. Introduction

Directional antennas have the potential to increase the capacity of a wireless network. In contrast to omni-directional antennas which radiate radio signal energy in all directions, directional antennas concentrate the electromagnetic energy in one direction. As a result, they can reduce co-channel interference, increase spatial reuse, and improve coverage range. For a given power level, they can provide a larger coverage range compared to omni-directional antennas. Links remain stable due to the increased signal strength and reduced multipath components [1]. Due to these advantages, directional antennas have been explored as a potential candidate to improve the capacity of wireless ad hoc networks, wireless mesh networks, etc. Directional antennas are also an integral part of millimeter wave (mmWave) networks. A salient feature of mmWave communications is the significantly higher path loss when compared with lower carrier frequencies. To mitigate this high path loss and high attenuation due to obstacles and to achieve good data rates at reasonable distances, it is necessary to use directional antennas both at the transmitters and the receivers [2], [3].

Since the usage of directional antennas reduces multi user interference, spatial reuse in networks can be enhanced to increase the throughput [1]. Spatial time division multiple access (STDMA) is a scheduling based channel access mechanism where a number of links that are well separated in space, transmit simultaneously to increase the throughput of the network. Various STDMA scheduling schemes have been proposed in literature for multi-hop networks [1], [4]–[7] and wireless personal area networks (WPANs) [2], [3], [8]–[10].

Existing STDMA scheduling methods have primarily been designed for network throughput enhancement [1]–[5], [7], [10]. Some other methods target to maximize the number of quality of service (QoS) satisfied flows [8]. However, many practical network deployments are characterized by heterogeneous node densities and users with diverse traffic load requirements. In these networks, some regions of the network may have a higher traffic demand than others. In such situations, adequate resources should be allocated to the crowded sections to maintain fairness in the network. This paper formulates STDMA scheduling of such networks as an optimization problem and proposes a heuristic scheduling method to obtain a real-time solution.

The main contributions of this paper can be summarized as follows.

- Zone formation methods are proposed to identify the crowded regions of the network.
- STDMA scheduling of the considered networks is formulated as a mixed integer nonlinear programming problem to provide priority to the highly loaded regions.
- A heuristic STDMA scheduling method is proposed to generate a schedule in real-time with low complexity. A performance comparison of the proposed method with the existing STDMA scheduling methods is also presented.

The rest of the paper is organized as follows. Section II discusses the related research. Section III introduces the system model. The zone formation methods to handle the crowded situations and the proposed STDMA scheduling method are presented in Sections IV and V, respectively. A performance evaluation of the proposed method is presented in Section VI. Section VII concludes the paper.

II. Related Work

In [1], [4], STDMA scheduling methods are proposed for multi-hop networks. A set of compatible links that satisfy interference requirements is assigned to each slot of a frame. While finding compatible links for a slot, priority is given to the links that received a lesser service. In [5], the performance of node-based and link-based STDMA scheduling mechanisms are evaluated under varying antenna lobe angles. In the node-based mechanism, one or more links originating from a node can be active in a slot. On the other hand, in the link-based mechanism, at most one link originating from a node can be active in each slot. In [6], a joint routing and concurrent transmission scheduling scheme is proposed for multi-hop wireless networks to satisfy the maximum fraction of each demand. A graph based representation of wireless networks is used to model the interference at a receiver in [7]. A truncated graph based scheduling algorithm for concurrent

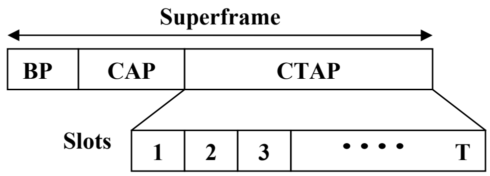

Fig. 1. Frame structure [8].

transmission is proposed to provide probabilistic guarantees on the throughput performance of a network.

STDMA scheduling has also been studied in the context of mmWave networks. In [8], concurrent transmission scheduling of mmWave WPANs is formulated as an optimization problem to maximize the number of flows whose QoS requirements are satisfied. To generate a schedule in real-time, a flip-based heuristic scheduling algorithm with a lower complexity is proposed. Concurrent transmission scheduling of multihop paths in mmWave WPANs is addressed in [10]. Concurrent transmission rate measurements as well as the actual STDMA schedule generation are formulated as optimization problems in [2], and sub-optimal heuristic solutions are also proposed. In D2DMAC [3] for mmWave small cells, STDMA scheduling of access and backhaul links is jointly addressed.

Different from the existing literature on STDMA scheduling, in this paper, we handle STDMA scheduling in directional WPANs/wireless local area networks (WLANs) with non-uniform traffic demands. The proposed zone formation methods help to identify the crowded regions of a network. To provide a better service to the highly loaded regions, the proposed scheduling algorithm allocates resources to zones in the decreasing order of their cumulative demands.

III. System Model

The network architecture considered in this paper resembles a typical WPAN/WLAN with a number of wireless devices (WDs) and one central coordinator, similar to the pico net coordinator (PNC), to coordinate the channel access among the WDs in the network. The available radio resource is divided into superframes along the time domain. As shown in Figure 1, each superframe consists of three periods [8]: beacon, contention access, and channel time allocation. During beacon periods (BPs), the PNC transmits synchronization information and distributes scheduling information in the network. During a contention access period (CAP), WDs send their traffic demands to the PNC and based on this information, the PNC generates a schedule for the channel time allocation period (CTAP) of the upcoming frame. During a CTAP, nodes transmit their data following the schedule communicated by the PNC. To handle with the deafness problem that can arise due to the usage of directional antennas, the PNC switches on all its beams during CAPs and only one beam during CTAPs [10].

The nodes are assumed to be half-duplex and deployed with steerable directional antennas [3]. An ideal flat-top antenna model with constant gain within the beamwidth and zero gain outside the beamwidth is used for directional antennas [11]. The PNC is aware of the topology [12] and locations of other nodes in the network [13] and only directional line-of-sight (LOS) transmissions are considered in this paper. The PNC can request the transmitter of each link to identify the interfering links during the beamforming (BF) process or based on the BF information (such as beam angles/directions) received from the nodes, the PNC can identify the interfering links of a link [9]. The channel conditions and topology are assumed to be static during a frame and this assumption is more acceptable for the networks with very small frame durations, LOS links, and low user mobility such as mmWave WPANs [8].

The signal to interference plus noise ratio (SINR) that determines the achievable data rate of a link is affected by various wireless channel impairments such as path loss, multipath fading, shadowing, etc [8]. Since we are assuming the nodes are deployed with directional antennas, the effect of multipath components is lesser compared to the scenario where omni-directional antennas are used [2]. We consider the average link throughput, since it is difficult to obtain instantaneous channel conditions of all active links and this throughput is mainly affected by path loss [8]. According to Shannon's channel capacity, the transmission rate of a link (i, j) can be calculated as:

$$R_{ij} \leq \kappa W \log_2(1 + P_r/(N_0 W + P_I)) \quad (1)$$

where $\kappa \in (0, 1)$ describes the efficiency of the transceiver design, W is the bandwidth, P_r is the received signal power, N_0 is the one-side power spectral density of white Gaussian noise, and P_I is the interference power [8]. P_r is given by $P_r = K P_\tau d_{ij}^{-\alpha}$, where $K = 10^{\Psi(d_{ref})/10}$ denotes the constant scaling factor, $\Psi(d_{ref})$ is the reference path loss at the reference distance d_{ref}, P_τ is the transmit power, d_{ij} is the distance between nodes i and j, and α is the path loss exponent [2], [8]. For links (i, j) and (x, y), the received power at node j from node x is given by

$$P_r^{xy,ij} = f_{xy,ij} K P_\tau d_{xj}^{-\alpha}, \quad (2)$$

where $f_{xy,ij}$ is 1 if nodes x and j direct their beams toward each other, and 0 otherwise. $f_{xy,ij}$ ensures the concurrent transmission condition as follows. Links (i, j) and (x, y) can transmit concurrently without interference (that is, $f_{xy,ij} = 0$) if and only if i and x are outside the beamwidth of y and j, respectively, or i (or x) does not direct its beam towards y (or j) if i (or x) is within the beamwidth of y (or j) [3]. Hence, P_I is given by

$$P_I = \rho \sum_{x \neq i,j} \sum_{y \neq i,j} f_{xy,ij} K P_\tau d_{xj}^{-\alpha}, \quad (3)$$

where ρ denotes the multi-user interference factor [8]. If c_{ij} is the transmission rate of link (i, j) and the minimum required SINR to support c_{ij} is $SINR_{min}(c_{ij})$, then link (i, j) can transmit concurrently with other links provided SINR of link (i, j), that is, $SINR_{ij} \geq SINR_{min}(c_{ij})$, where

$$SINR_{ij} = \frac{K P_\tau d_{ij}^{-\alpha}}{N_0 W + \rho \sum_{x \neq i,j} \sum_{y \neq i,j} f_{xy,ij} K P_\tau d_{xj}^{-\alpha}}. \quad (4)$$

Here, link (x, y) is a representative of the links that are

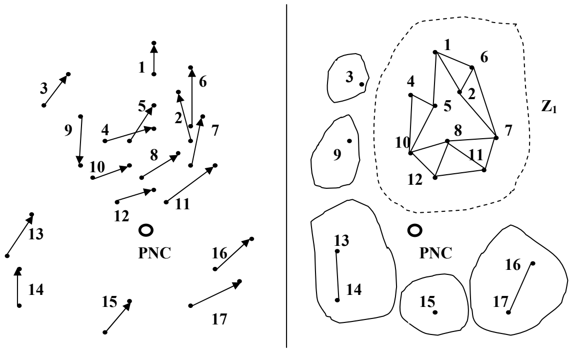

Fig. 2. Network showing directed links (left) and its conflict graph (right).

scheduled to transmit concurrently with link (i, j).

IV. Identification of Crowded Zones

Consider the network shown in Figure 2. In its conflict graph, nodes represent the links of the network and the edges show the interference relationship among the links. In the left part of Figure 2, links are marked with numbers for presentation clarity. In zone Z_1, marked with the dotted outline curve, the number of links as well as the average number of interfering links per link is very high in comparison to other zones. Each scheduled link of Z_1 blocks a large number of other links from the same zone. As a result, links in Z_1 may have higher backlogs when compared with the links in other zones. Hence, it is important to identify and provide adequate resources to such zones.

To identify the crowded zones, we utilize the interference information of various links in the network. In the remaining discussion, the number of interfering links of a link is referred as the *interference* of the link. The PNC initiates the zone creation process if the interference of at least one link is more than two. The link with the highest interference, say e_1, and its interfering links are grouped into a zone, say Z_1. Among the remaining links, the PNC repeatedly identifies the links that are interfered by two or more links of zone Z_1 and includes them in Z_1, and concludes the formation of Z_1 when no such link is found. The same process is repeated until all the links in the network are assigned to some zone. A link with zero interference forms a zone of which it is the sole member. This method is called the "two-link based zone formation" method. The pseudo code of this method is shown in Algorithm 1

Zones can also be formed by using other criteria such as single-hop neighborhood, two-hop neighborhood, and antenna beamwidth as explained below:

Two-hop based zone formation: Link e_x with the highest interference and its one and two-hop neighbors in the conflict graph form the first zone. The same process is repeated on the remaining links until all links are assigned to some zone.

Single-hop based zone formation: The link with the highest interference and its interfering links are grouped as a zone. This process is repeated on the remaining links.

Beamwidth based zone formation: The link with the highest interference and its interfering links are grouped as one zone, say Z_1. The PNC repeatedly identifies the links that are interfered by two or more links of zone Z_1 and adds them (one by one) to Z_1, until the largest angle subtended by any two nodes of Z_1 at the PNC is more than the beamwidth of the antennas used in the network or no further interfering links exist. This process is repeated on the remaining links.

Algorithm 1 Two-Link Based Zone Formation Algorithm

BEGIN:

initialization: E is the set of links; $I(i, j)$ represents the interference of link (i, j); NH_{ij} represents neighbors of (i, j) in the conflict graph;
while $E \neq \phi$ **do**
  $Z = \phi$; $NH_{temp} = \phi$;
  find $(i, j) \in E$ with the highest $I(i, j)$;
  $Z = Z \cup \{NH_{ij}\}$;$E = E - \{NH_{ij}\}$;
  $NH_{temp} = NH_{temp} \cup NH_{ij}$; exit = false;
  while exit == false **do**
    find $(x, y) \in E$ that is interfered by two or more links of NH_{temp}
    if $(x, y)\ != \phi$ **then**
      $Z = Z \cup \{(x, y)\}$;$E = E - \{(x, y)\}$;
      $NH_{temp} = NH_{temp} \cup \{(x, y)\}$;
    else
      exit = true;
    end if
  end while
  Output Z;
end while

END;

V. STDMA Scheduling in WPANs/WLANs

Consider a network with n active links, where the traffic demand of link (i, j) is represented by l_{ij}, and c_{ij} represents its transmission rate. The sum of the demands of all links in zone k is denoted by L_k and called the cumulative demand. The optimal transmission schedule should accommodate the traffic demands with the least number of slots or should minimize the unsatisfied traffic demand after the completion of scheduling. A STDMA schedule consists of a set of pairings and can be represented as:

$$\Pi = \theta_1 S^1 + \theta_2 S^2 + \cdots + \theta_m S^m \tag{5}$$

where θ_t represents the duration of the t-th pairing in terms of number of slots and S^t represents the set of links to participate in data transmission in the t-th pairing.

The objective behind grouping links into zones in Section IV is to identify highly loaded regions and provide them appropriate resources while performing scheduling. To achieve this, zones should be considered for scheduling in the decreasing order of their cumulative demands. Let a^t_{ijz} be an indicator variable that is set to 1 if link (i, j) of zone z is scheduled for data transmission in the t-th pairing, and 0 otherwise. The function $g(t')$ returns 0, if $SINR_{xy} < SINR_{min}(c_{xy})$ for any link (x, y) in the set t' of concurrent links, and 1 otherwise. l^t_{ijz} $(= l_{ij} - \sum_{t_1=1}^{t} \theta_{t_1} a^{t_1}_{ijz} c_{ij})$ represents the residual load of link (i,j) of zone z after considering the bandwidth allocations in pairings 1 to t and $l^0_{ijz} = l_{ij}$.

The optimal scheduling problem (**P1**) can be formulated as:

$$\min \sum_{t=1}^{m} \theta_t \quad (6)$$

such that

$$\sum_{t=1}^{m} a^t_{ijz} \begin{cases} \geq 0, \ \leq \lceil l_{ij}/c_{ij} \rceil, & \text{if } l_{ij} > 0 \\ = 0, & \text{if } l_{ij} = 0 \end{cases} \forall\ i,j,z \quad (7)$$

$$a^t_{ijz} \in \begin{cases} \{0,1\}, & \text{if } l_{ij} > 0 \\ \{0\}, & \text{if } l_{ij} = 0 \end{cases} \forall\ i,j,z,t \quad (8)$$

$$\sum_{t=1}^{m} \theta_t a^t_{ijz} c_{ij} \begin{cases} \geq 0, & \text{if } l_{ij} > 0 \\ = 0, & \text{if } l_{ij} = 0 \end{cases} \forall\ i,j,z \quad (9)$$

$$\sum_{j=1}^{n} (a^t_{ijz} + a^t_{jiz}) \leq 1\ \forall\ i,z,t \quad (10)$$

$$SINR^t_{ij} \geq SINR_{min}(c_{ij})\ \forall\ i,j,t \quad (11)$$

$$a^t_{ijz_1} > a^t_{xyz_2},\ \text{if} \begin{cases} l^{t-1}_{ijz_1} > 0, g(t' \cup (i,j)) > 0 \\ l^{t-1}_{xyz_2} > 0, g(t' \cup (x,y)) > 0 \\ g(t' \cup (i,j) \cup (x,y)) = 0 \end{cases}$$

$$\text{where } t' = \bigcup_{\substack{(u,v)\in b,\ a^t_{uvb}>0, \\ (L_b \geq L_{z_1} > L_{z_2})}} (u,v)\ \forall\ i,j,x,y,z_1,z_2,t. \quad (12)$$

Conditions (7) to (9) indicate that a link is allocated bandwidth if and only if the load of the link is more than zero and the total bandwidth allocated to a link can span over multiple pairings. Condition (10) ensures that adjacent links cannot be part of the same pairing. Condition (11) indicates that the SINR of all links scheduled in a pairing should be more than their minimum required SINR values. Condition (12) ensures the prioritized handling of links from the highly loaded zones as follows. Let $(u,v) \in b$ be a link that is scheduled in the t-th pairing. If $(i,j) \in z_1$ and $(x,y) \in z_2$ be two links that interfere with each other and do not interfere with (u,v) where $L_b \geq L_{z_1} > L_{z_2}$, for all u,v, and b, then priority should be given to link (i,j).

The problem **P1** is a mixed integer nonlinear programming problem and it is generally NP-hard. Consider a network consisting of five nodes (1 to 5). The traffic demands of various nodes in the network can be represented in the form of a demand matrix D:

$$D = \begin{pmatrix} 0\,0\,0\,0\,0 \\ 4\,0\,2\,0\,0 \\ 0\,0\,0\,0\,0 \\ 0\,0\,2\,0\,2 \\ 0\,0\,0\,0\,0 \end{pmatrix}, \quad C = \begin{pmatrix} 0\,0\,0\,0\,0 \\ 2\,0\,1\,0\,0 \\ 0\,0\,0\,0\,0 \\ 0\,0\,1\,0\,2 \\ 0\,0\,0\,0\,0 \end{pmatrix} \quad (13)$$

where row i represents the pending traffic demands (in terms of number of packets) that node i needs to transmit to the other nodes in the network. Matrix C in (13) is the transmission rate matrix, and the element at position (i,j) represents the number of packets node i can transmit to node j in one slot. In this network, we assume that when a link (i,j) is active concurrently with other links, its SINR is sufficient to support its transmission rate. When we solve the scheduling problem **P1** for this example using an open-source solver YALMIP [14] on a desktop computer with an Intel Xeon E5-1650 CPU and 32 GB random access memory (RAM), it takes 52 seconds on average to generate the schedule S given below:

$$S = 2 \begin{pmatrix} 0\,0\,0\,0\,0 \\ 1\,0\,0\,0\,0 \\ 0\,0\,0\,0\,0 \\ 0\,0\,1\,0\,0 \\ 0\,0\,0\,0\,0 \end{pmatrix} + 1 \begin{pmatrix} 0\,0\,0\,0\,0 \\ 0\,0\,1\,0\,0 \\ 0\,0\,0\,0\,0 \\ 0\,0\,0\,0\,1 \\ 0\,0\,0\,0\,0 \end{pmatrix} + 1 \begin{pmatrix} 0\,0\,0\,0\,0 \\ 0\,0\,1\,0\,0 \\ 0\,0\,0\,0\,0 \\ 0\,0\,0\,0\,0 \\ 0\,0\,0\,0\,0 \end{pmatrix}. \quad (14)$$

In S, each matrix represents a pairing, and the value in front of each matrix represents the duration of the corresponding pairing. From the first matrix of schedule S, one can infer that in the first pairing, links $(2,1)$ and $(4,3)$ communicate concurrently for 2 slots. Since solving NP-hard problems using optimization software is time intensive, we develop an efficient heuristic scheduling method to obtain a STDMA schedule in real-time.

A. *Heuristic STDMA Scheduling Method*

To maximize the spatial reuse, intuitively, links should be considered for scheduling in the increasing order of their interference. It is also important to give adequate resources to the links with higher traffic demand to provide a fair bandwidth allocation. In order to address these two goals, the ratio of the load and the interference of each link (denoted by "μ") is used as the link selection metric during pairing generation. The μ value of a link combines the two factors (load and interference) that affect the scheduling into one quantity.

The proposed zone-based STDMA scheduler ("STDMAZ") starts each pairing generation from the zone, say Z_{H1}, with the highest cumulative demand. From zone Z_{H1}, the link e_{h11} with the highest μ value is selected and scheduled first. Next, the link, say e_{h12}, with the next highest μ value is selected and scheduled in the pairing if the condition for concurrent transmission is not violated for any of the links in the pairing. This cycle is repeated until all the links in zone Z_{H1} are tested for concurrent transmission. After that, among the remaining zones, the zone, say Z_{H2}, with the next highest cumulative demand is selected and the whole process is repeated on zone Z_{H2}.

After considering all the zones in the order of their cumulative demands, the minimum transmission time among all scheduled links in the pairing is set as the duration of the pairing. The residual traffic demands of the scheduled links and the number of free slots available in the frame are updated. This pairing generation process is repeated until either all links are scheduled successfully or there are no more free slots to continue the pairing generation process. The pseudo code for STDMAZ is shown in Algorithm 2. In the worst case, the while loop in line 2, the for loop in line 4, and the for loop in line 8 can have $O(T)$, $O(n)$ and $O(n)$ iterations, respectively. Hence, the complexity of the algorithm is $O(Tn^2)$. For the

Algorithm 2 STDMAZ Scheduling Algorithm

BEGIN:

1: initialization: l'_{ij} is the load of link (i, j) in terms of slots; PNC forms zones $z_1, z_2, \cdots, z_k$ and $L_{z_1} \geq L_{z_2} \cdots \geq L_{z_k}$; T is the total number of slots; $t = 0$;
2: **while** $T > 0$ and ($z_1 \neq \phi$ || $z_2 \neq \phi$ || .... || $z_k \neq \phi$) **do**
3: $\quad$ $t = t + 1$; $load_{min} = 0$; $S^t = \phi$;
4: $\quad$ **for** all $z_H = z_h$, ($h := 1$ to k) and $z_H \neq \phi$ **do**
5: $\quad\quad$ **while** $z_H \neq \phi$ **do**
6: $\quad\quad\quad$ find $(i, j) \in z_H$ with the highest μ value;
7: $\quad\quad\quad$ $S^t = S^t \cup \{(i, j)\}$; $z_H = z_H - \{(i, j)\}$;
8: $\quad\quad\quad$ **for** all $(x, y) \in S^t$ **do**
9: $\quad\quad\quad\quad$ **if** $SINR_{xy} < SINR_{min}(c_{xy})$ **then**
10: $\quad\quad\quad\quad\quad$ $S^t = S^t - \{(i, j)\}$; Go to line 5;
11: $\quad\quad\quad\quad$ **end if**
12: $\quad\quad\quad$ **end for**
13: $\quad\quad\quad$ **if** ($load_{min} == 0$ || $l'_{ij} < load_{min}$) **then**
14: $\quad\quad\quad\quad$ $load_{min} = l'_{ij}$;
15: $\quad\quad\quad$ **end if**
16: $\quad\quad$ **end while**
17: $\quad$ **end for**
18: $\quad$ **if** $T < load_{min}$ **then**
19: $\quad\quad$ $load_{min} = T$;
20: $\quad$ **end if**
21: $\quad$ $T = T - load_{min}$;
22: $\quad$ **for** all $(i, j) \in S^t$ **do**
23: $\quad\quad$ $l'_{ij} = l'_{ij} - load_{min}$; remove (i, j) from the corresponding zone provided $l'_{ij} = 0$;
24: $\quad$ **end for**
25: $\quad$ Output S^t and $load_{min}$;
26: **end while**

END;

example given in (13), STDMAZ gives the same schedule as YALMIP.

VI. Simulation Results

Performance of the proposed method is evaluated using our simulator coded in C++. Due to the increasing interest in mmWave networks, the performance of STDMAZ is evaluated in the context of a mmWave WPAN deployed with a large number of devices that communicate at high data rates. We consider a network where 80 nodes are distributed in a square region of area 10×10 m^2. The PNC is located at the center of the area. The system bandwidth is 1200 MHz and background noise level is -134 dBm/MHz [15]. Each node is equipped with a directional antenna. The beamwidth of antennas is 60^o and the transmission power of nodes is set as 0.1 mW. The path loss is 71.5 dB at the reference distance of 1.5 m and the path loss exponent is 2 [16]. Slot duration is 18 μs and the number of slots in data transmission period is 1000 [10]. The presented results are averaged over 25 simulation runs and each simulation lasts for 10 minutes.

If node j is within the transmission range of node i, then a flow can be established between i and j. Flows are established between randomly selected nodes and the number of flows in the network is varied from 10 to 50. The bandwidth requirements of the flows are uniformly distributed between 1.5 and 3.5 Gbps. During each simulation run, based on the interference information of various links, the PCN forms zones. Based on the bandwidth requests of various flows, the PNC generates a STDMA schedule for the data transmission period of each frame.

The performance of the STDMAZ scheduler is compared with that of a STDMA scheduler ("STDMA-HD") proposed in the literature [2]. In STDMA-HD, the network is represented as a directed and weighted multigraph. A link with pending traffic demand becomes an edge in the graph and its normalized demand (that is, the demand converted into number of slots) is its weight. During each pairing generation, edges are considered in the decreasing order of their normalized weights.

Two sets of simulation experiments are conducted. In one set, called "non-crowded (NC)", nodes are uniformly deployed in the considered region and in the second set, called "crowded (C)", $2/3$ of the nodes in the network are uniformly deployed in one quarter of the area to create a network with high node density in one section. The average number of successfully scheduled flows and the average percentage of satisfied demand from the highly loaded zone are considered as the performance metrics. If the demand of a flow is fulfilled completely, then it is called a successfully scheduled flow.

In the "crowded" scenario, the interference of a link that is a part of the crowded region is higher compared to the interference of a link in the "non-crowded" scenario. As a result, the number of flows scheduled in the "non-crowded" scenario is more than that in the "crowded" scenario, for both STDMAZ and STDMA-HD, as shown in Figures 3 and 4. However, STDMAZ, with the help of its link selection metric, successfully schedules a larger number of flows compared to STDMA-HD. With STDMAZ, the links with lower demands and higher interference may not receive service immediately. As time progress, their demands accumulate and μ values increase, and they ultimately get service. Figures 3 and 4 show the results for two zone formation methods only. Results for the other zone formation methods are not included due to space limitations.

The proposed method satisfies a larger fraction of the demand from the highly loaded zones than STDMA-HD, as shown in Figures 5 and 6, by prioritizing the links from the highly loaded zones. Due to higher interference of the links in the crowded section, the satisfied demand in the "crowded" scenario is lower than that of the "non-crowded" scenario.

The two-link based zone formation method creates bigger zones with larger number of links when compared with other methods. When the zone sizes are large, the difference between the number of links with unsatisfied demand in the "crowded" and "non-crowded" scenarios is high. As a result, in the case of two-link based zone formation method, the difference between the satisfied demand in the "non-crowded" and "crowded" scenarios is high (see Figure 6) when compared with beamwidth based zone formation method (see Figure 5).

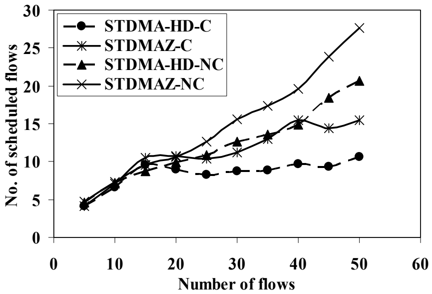

Fig. 3. Number of flows vs number of scheduled flows (single-hop based zone formation).

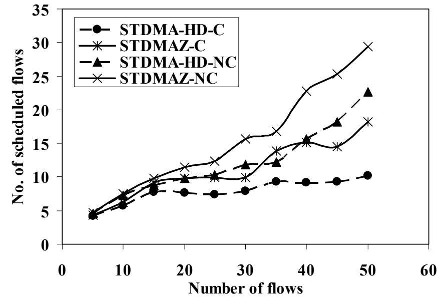

Fig. 4. Number of flows vs number of scheduled flows (two-hop based zone formation).

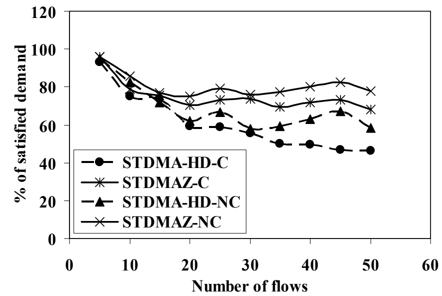

Fig. 5. Number of flows vs percentage of satisfied demand (beamwidth based zone formation).

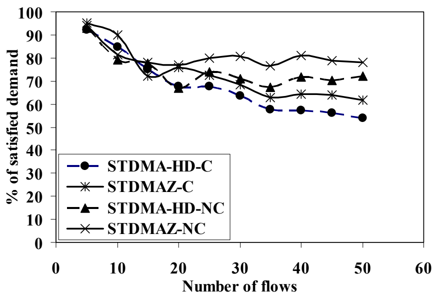

Fig. 6. Number of flows vs percentage of satisfied demand (two-link based zone formation).

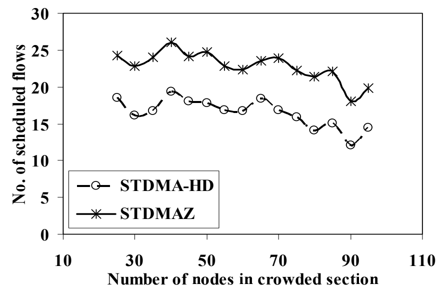

Fig. 7. Number of nodes in the crowded section vs number of scheduled flows (beamwidth based zone formation).

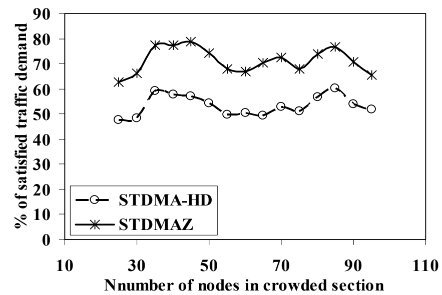

Fig. 8. Number of nodes in the crowded section vs percentage of satisfied demand (beamwidth based zone formation).

Figures 7 and 8 show the simulation results for the scenarios where the number of nodes in the crowded section is increased from 25 to 95. The number of nodes in the network is 100 and the number of flows is 50. With the help of its link selection metric and by prioritizing the highly loaded zones, STDMAZ consistently shows a better performance compared to STDMA-HD in terms of the considered performance metrics.

VII. Conclusions

This paper proposes a STDMA scheduling method for WPANs/WLANs with non-uniform traffic demand. Zone formation methods to identify highly crowded regions, and a STDMA scheduling algorithm that tries to maximize the number of concurrent transmissions while jointly considering the load and interference for each link are proposed. The performance of the proposed method is evaluated through simulations and compared with existing methods. With the help of link selection metric and prioritized handling of the zones with higher demands, the proposed method shows a better performance.

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