Distributed Scheduling based Dimensioning Mechanism for Wireless Mesh Networks

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Abstract— **In wireless mesh network (WMN), especially in distributed (infrastructure-less) mode, common channel access results in inter-node interference which limits the available capacity of the network. To facilitate the growth of the network (i.e., addition of new routers/nodes), it is therefore necessary to identify the maximum allowable system capacity that can be achieved without degrading the performance. In this paper, we propose a dimensioning mechanism for a 802.16 based distributed WMN where we utilize the results of [1] to analyze the system capacity (conversely node capacity) in bottleneck conditions. To guarantee appropriate throughput for the bottleneck and its neighboring nodes, the network bound (maximum number of added nodes, h^u) is set accordingly. Simulations results demonstrate the validity of the proposed dimensioning algorithm and enables network providers or operators to select h^u in accordance to their system requirements.**

I. INTRODUCTION

In the past few years, the soaring demand for inexpensive high speed Internet has given rise to interest into developing new technologies. Among the recent developments, Wireless Mesh Network (WMN) offers one of the most promising technologies because of its cost-effective infrastructure and utilization [2]. Consisting of interconnected mesh nodes (including clients and routers), the WMN offers data relaying capability across the entire network, self-organization in the absence of an infrastructure and coverage extension, thereby making it a strong contender for the next generation Internet [3]. The two main radio technologies adopted for supporting the interworked mesh architecture include IEEE 802.16 and IEEE 802.11 [4] . While IEEE 802.16 (often referred to as WiMAX (Worldwide Interoperability for Microwave Access)) can provide metropolitan area coverage with performance comparable to the traditional asynchronous subscriber line (ADSL), IEEE 802.11 (often referred to as Wi-Fi) is limited to small coverage area only (e.g., hot spots, buildings etc.). Since the 802.16 mesh nodes (clients and routers) utilize the same access channels (but usually different from 802.11 [5]), network growth in terms of new nodes introduction enforces additional interference and affects the available network capacity. Here, capacity refers to throughput. This is particularly important in cases of bottlenecks. In WMN, a bottleneck is defined as a node that carries data traffic to and from a subset of mesh nodes. Since all traffic traverses through the bottleneck node, the capacity of the neighboring nodes (i.e., available throughput) is limited by this subset and the inter-node interference. To resolve this issue and achieve optimal network performance, smart designing of this subset (also referred to as dimensioning)is required.

In this paper, we propose a dimensioning mechanism that derives an approximate bound (maximum limit) of the subset (defined earlier) in a 802.16 based distributed WMN. The approximation is based on average inter-node interference within the neighborhood of the bottleneck and provides performance measures for each node so as to meet the quality of service (QoS). The algorithm incorporates the distributed scheduling mechanism introduced in [1] and utilizes this to analyze the performance variation of the network as new nodes are connected to the architecture. Our key contribution therefore lies in providing a mechanism to estimate the performance variation when nodes have different transmission interval but identical hold-off time. This is in contrast to [1] which provides measurements for performance variation in collocated scenarios where all nodes have identical performance and are one-hop neighbors of each other. Furthermore, the proposed algorithm in this paper also derives an upper bound for network growth in bottleneck conditions (not addressed in [1]).

The remainder of this paper is organized as follows. In Section II, the general structure of the WMN is outlined. Section III presents a brief overview of the IEEE 802.16 distributed scheduling mechanism. The proposed network architecture is explained and dimensioned in Section IV. Performance evaluation of the proposed algorithm is presented in Section V, followed by some concluding remarks.

II. OVERVIEW OF WIRELESS MESH NETWORK

Within the mesh topology, the core of the WMN constitutes of mesh routers and mesh clients, and is connected over multiple links. While mesh clients (i.e. client nodes) facilitate routing functionalities, mesh routers operate as access points (offering connectivity to mesh clients and other mesh routers). Interconnection among these nodes therefore provides many advantages in WMN such as reliability, self-organization, coverage extension in blind spots, and so on [6]. Since the key idea behind WMN is to offer an interworked self-healing broadband infrastructure for different traffic regions (urban and rural), WMN can unite the two most popular Internet systems namely IEEE 802.16 (provides wide coverage and backhaul infrastructure) and IEEE 802.11 (hotspots) in a multi-layer (dual system) architecture. Fig. 1 depicts such a system

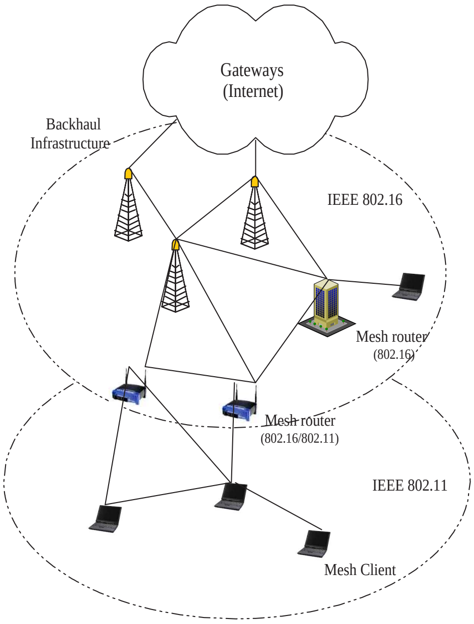

Fig. 1. General layout of a WMN.

with 802.16 and 802.11 nodes and their corresponding mesh clients clearly identified. Note that the routers can have dual protocol stack (802.16/802.11) and can support both forms of coverage. Assuming that IEEE 802.16 and IEEE 802.11 use different frequency bands i.e., 5 GHz and 2.4 GHz respectively (as is commercially utilized), it can be concluded that there is no mutual interference between these two systems and accordingly does not affect the WMN performance. Based on the fact that 802.16 provides the backhaul infrastructure, our investigation is limited to defining the upper bound of the node subset that can be accommodated by a 802.16 mesh router (bottleneck). This entails the consideration of a data rate range of 32-130 Mbps, depending on the coding, modulation and transmission bandwidth. However achieving such a high data rate in an interference-limited system like the 802.16 based WMN with shared channel access requires proper scheduling for data transmission. Traditionally, in IEEE 802.16, control messages and data packets are transmitted in the same channel but in different time subframes. Therefore the scheduling of the data subframes are carried out through the exchange of the control messages.

III. DISTRIBUTED SCHEDULING IN IEEE 802.16

As mentioned earlier, IEEE 802.16 [7] is a promising technology for providing wireless broadband service to a metropolitan area with performance comparable to the traditional asynchronous digital subscriber line (ADSL). Since all nodes share the same wireless channels, careful scheduling for channel access is required to maximize the system performance. Usually either a centralized method or a distributed scheduling mechanism is adopted for IEEE 802.16 in mesh mode (as is widely recommended for multihop wireless networks). Although the base station manages the scheduling process (all control packets traverse through the base station) in the centralized method, a distributed system is preferable due to the reduction in the signaling overhead (especially for connection setup) and the efficiency in data transmission [1].

In the distributed approach, every node has the scheduling information of its neighbors (as far as two hops away). Based on this information nodes compete for channel access using a pseudo-random election process which is followed by a three-way handshake procedure that allocates data subframes. When a node wins the election, it will be granted with $V = 2^{Exp}$ time slots for transmitting its schedule. The node is not allowed to transmit for the duration of its hold-off time ($H = 2^{Exp+4}$) after this transmission. In the above expressions, Exp (exponent value) can have a value from zero to seven and is managed by every node itself. Note that the bandwidth available to each node is limited by the amount of interference emanating from adjacent competing nodes. Therefore the maximum achievable bandwidth for node k in a network with N competing nodes can be derived as follows [8],

$$\lambda = \frac{\theta \cdot \rho \cdot S_{MS}}{\tau_{T_k}} \tag{1}$$

where θ is the maximum number of timeslots requested within a single channel access request, ρ is the number of bytes transmitted within one orthogonal frequency division multiplexing (OFDM) symbol, S_{MS} is the number of OFDM symbols per minislot, while τ_{T_k} denotes the interval between successive transmissions respectively. In [8], for mesh distributed scheduling (MSH-DSCH), τ_{T_k} is defined as,

$$\tau_{T_k} = \tau_{S_k} \cdot \frac{\nu \cdot (\varsigma \cdot 4 + 1)}{\varsigma \cdot 4 \cdot \Gamma} \tag{2}$$

where ν and ς refer to network parameters $FrameLength$ and $SchedulingFrames$, while Γ and τ_{S_k} denote the number of distributed scheduling messages and the slot interval between successful transmissions respectively. Based on the hold-off time, τ_{S_k} (i.e., transmission interval) in (2) can therefore be written as [1],

$$\tau_{S_k} = H_k + S_k \tag{3}$$

where S_k is the contention period (in slots) of node k. Since an exact expression for S_k is difficult to derive, an approximate solution (i.e., expected value or average) is provided in [1] as follows,

$$\begin{aligned} E\left[S_k^N\right] = & \sum_{j=1, j\neq k, Exp_j \geqslant Exp_k}^{N_k^{Known}} \frac{V_j + E[S_k^N]}{H_j + E\left[S_j\right]} \\ & + \sum_{j=1, j\neq k, Exp_j < Exp_k}^{N_k^{Known}} 1 + N_k^{Unknown} + 1 \end{aligned} \tag{4}$$

Here, N_k^{Known} and $N_k^{Unknown}$ denote the set of neighbors (one and two hops away) of the node k with known and unknown scheduling time.

IV. THE PROPOSED DIMENSIONING ALGORITHM

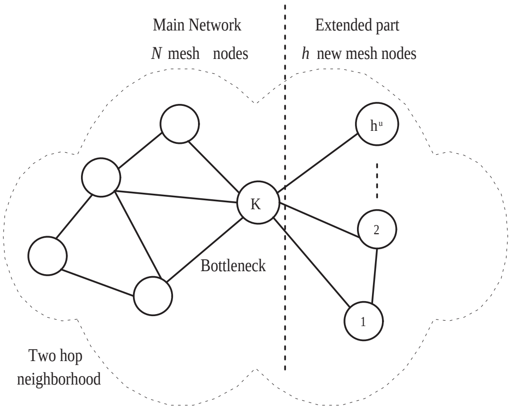

Fig. 2. Network extension of WMN in the bottleneck neighborhood.

Since increasing the number of nodes in WMN results in increased interference and subsequent performance degradation, network extension (alternatively node addition) must be carried out in a planned manner. In this section, we analyze the dimensioning aspect of a WMN with known architecture (knowledge of existing nodes and their interference level). As shown in Fig. 2, a particular instance of the network extension is investigated where a number of nodes (i.e., mesh routers and mesh clients) are connected to a particular 802.16 router (referred to as a bottleneck). Since traffic in the extended part traverse through node k , the performance of the subset (i.e., new mesh nodes here) is limited by this node (functioning as a bottleneck).

A. Dimensioning network extension

Let us assume that, for node k, the average interval (expected value) between successful transmissions (excluding the hold-off time) is known *a priori* and is given by $E[S_k^{N_k^{Known}}] \sim E[S_k^N]$ where N represents the set of neighbors (maximum two hops away). Therefore as a new node is attached to node k, it not only affects its performance but also other nodes in the subset. Let h^u denote the maximum number of nodes (the size of the subset) that can be added to node k. Our aim is to calculate the performance variation of node k as h changes. Performance is quantified in terms of the overall interference from the neighboring nodes and the resulting available throughput. We assume that these nodes are placed within the coverage area of node k (defined by its two hop neighborhood). Even though $N_k^{Unknown}$ can be an element in the node subset, the small variance in the subset size from $N_k^{Unknown}$ will not affect the system performance significantly [1]. Hence $N_k^{Unknown} = 0$ in the proposed algorithm. In addition, the proposed algorithm considers all nodes within the set to have identical hold-off exponent (Exp).

Within such a domain structure (defined by node k and its two hop neighbors), the proposed dimensioning algorithm finds the average contention period ($\tilde{E}\left[S^N\right]$) for N nodes in the neighborhood (including node k). Then it utilizes this value to estimate the transmission interval as a new node gets connected, thereby offering a performance measure for the network extension. A step-by-step description of the algorithm is given below.

First, considering the abovementioned assumptions (including $\sum_{j=1,j\neq k,Exp_j<Exp_k}^{N_k^{Known}} 1 = 0$ since for simplicity purposes all intervals are considered equal in the neighborhood i.e., $Exp_j = Exp_k$), (4) can be simplified into the following expression,

$$E\left[S_k^N\right] = \frac{1+2^{Exp}\cdot Y}{1-Y} \tag{5}$$

where Y is defined as,

$$Y = \sum_{j=1,j\neq k}^{N} \frac{1}{H+E\left[S_j^N\right]} \tag{6}$$

Here Y plays a significant role in providing the channel access rate of the competing nodes in the neighborhood. Hence adding new nodes degrades $E\left[S_k^N\right]$ of each node, thereby reducing the value of Y. Using the definition of harmonic mean, Y can be represented as $\frac{N-1}{H+\tilde{E}\left[S_j^N\right]}$ where $\tilde{E}\left[S_j^N\right]$ denotes average contention period of all j nodes ($E\left[S_j^N\right] : j \neq k$) within the neighborhood. Equation (5) can then be expressed as,

$$E\left[S_k^N\right] = \frac{1+2^{Exp}\cdot\frac{N-1}{H+\tilde{E}\left[S_j^N\right]}}{1-\frac{N-1}{H+\tilde{E}\left[S_j^N\right]}} \tag{7}$$

Having defined the successful transmission interval for node k (i.e., $H+E\left[S_k^N\right]$), the average contention period for the other nodes in the neighborhood $\left(\tilde{E}\left[S_j^N\right]\right)$ can be derived from (7). Since the hold-off time is constant and does not change, the average transmission interval ($H+\tilde{E}\left[S^N\right]$) is mainly affected by $\tilde{E}\left[S^N\right]$. Therefore the average harmonic mean contention period ($\tilde{E}\left[S^N\right]$) for all nodes in the neighborhood can be written as,

$$\tilde{E}\left[S^N\right] = \frac{N}{\frac{N-1}{\tilde{E}\left[S_j^N\right]}+\frac{1}{E\left[S_k^N\right]}} \tag{8}$$

Because $E\left[S_j^N\right] : j \neq k$ is unknown in (7), it is difficult to estimate effects of a node introduction on the neighborhood performance and in particular the performance of node k. As such, in this paper we consider an approximate method. In the proposed approximation, the two-hop neighborhood is reduced to a collocated form where nodes are considered to be one hop neighbors of each other. This stems from the fact that transmission interval of nodes are similar in the general topology (two-hop neighborhood), and collocated scenario (the impact of unknown nodes is neglected as mentioned before) as per [1]. Hence, the performance of a collocated scenario can be utilized to estimate the approximate performance of the general topology. With such approximation, the mean contention period (approx.) of nodes is given as the following (derived from (5) where $V = 2^{Exp}$ and $H = 2^{Exp+4}$),

$$\tilde{E}\left[S^N\right] = \frac{N - H + \sqrt{(N-H)^2 + 4(H + N \cdot V - V)}}{2} \tag{9}$$

In case of a new node introduction, it is necessary to calculate the approximate performance changes of a collocated scenario. Υ offers this performance measure by taking the ratio of (9) with $N+1$ and N nodes respectively as follows,

$$\begin{aligned}\Upsilon &= \frac{\tilde{E}\left[S_c^{N+1}\right]}{\tilde{E}\left[S_c^N\right]} \\ &= \frac{(N+1)-H+\sqrt{(N+1-H)^2+4(H+(N+1)\cdot V-V)}}{N-H+\sqrt{(N-H)^2+4(H+N\cdot V-V)}}\end{aligned} \tag{10}$$

Υ can be utilized to estimate the performance changes in the general topology, therefore, as a new node is connected, the average contention period for the entire neighborhood can be appraised from (10) as $\tilde{E}\left[S^{N+1}\right] = \Upsilon \cdot \tilde{E}\left[S^N\right]$. Furthermore, (7) and (8) can be re-written (with $N+1$ nodes) as follows to calculate the average transmission interval (using harmonic mean),

$$H + E\left[S_k^{N+1}\right] = H + \frac{1 + 2^{Exp} \cdot \frac{N+1-1}{H+\tilde{E}\left[S_j^{N+1}\right]}}{1 - \frac{N+1-1}{H+\tilde{E}\left[S_j^{N+1}\right]}} \tag{11}$$

$$H + \tilde{E}\left[S^{N+1}\right] = \frac{N+1}{\frac{N}{H+\tilde{E}\left[S_j^{N+1}\right]} + \frac{1}{H+E\left[S_k^{N+1}\right]}} \tag{12}$$

Since $\tilde{E}\left[S_j^{N+1}\right]$ and $E\left[S_k^{N+1}\right]$ are unknown, solving them for the above equations derives the contention period of node k as follows,

$$E[S_k^{N+1}] = \frac{-B - \sqrt{B^2 - 4AC}}{2A} \tag{13}$$

where

$$\begin{aligned} A &= 1 + N - \tilde{E}\left[S^{N+1}\right] - H \\ B &= (N+1)(V+H) - (\tilde{E}\left[S^{N+1}\right] + H).H \\ C &= VNH + h.H.V - (\tilde{E}\left[S^{N+1}\right] + H).V \\ &\quad + (\tilde{E}\left[S^{N+1}\right] + H).H \end{aligned}$$

Note that this algorithm evaluates the transmission interval of node k when a new node is connected. Hence, in the case of h nodes introduction, the performance changes of node k can be anticipated by iterating the same algorithm (adding one node at each iteration).

B. Bottleneck Performance

Since the entire traffic to and from the node subset is carried by the bottleneck, the amount of bandwidth available in node k is shared among the nodes. Intuitively, increasing the number of nodes in the subset (i.e., h) therefore results in a decrease of their capacity share. In addition, performance of node k itself degrades due to the large number of competing nodes. As each node expects to receive the minimum QoS, the number of added nodes should be limited, subject to acceptable inter-node interference. In this section, our aim is to investigate this problem by estimating an upper bound of the node subset (h^u). Since optimal services for users vary in different networks in terms of bandwidth, throughput, delay and so on, we define T^e as the minimum throughput that each user in the subset expects to receive from the bottleneck. Therefore h^u can be calculated with the help of the equations described in the previous section. Let $\lambda_k^{N+h^u}$ denote the maximum achievable bandwidth (or throughput) of node k with $N + h^u$ neighbors. Since it is the sum of the achievable throughput for all users in the subset, it can be represented as follows,

$$\lambda_k^{N+h^u} = h^u \cdot T^e \tag{14}$$

Hence, applying (14) in (1), (2) and (3), we get the following expression,

$$E[S_k^{N+h^u}] = \frac{\theta \cdot \rho \cdot S_{MS}}{\frac{\nu\cdot(\varsigma\cdot 4+1)}{\varsigma\cdot 4\cdot\Gamma} \cdot h^u \cdot T^e} - H \tag{15}$$

While $E[S_k^N]$ is known, applying the algorithm described in the previous section on the above equation, $E[S_k^{N+h^u}]$ and h^u can be calculated by using fixed point iteration.

V. PERFORMANCE EVALUATION

In this section, we analyze the changes in the transmission interval of a bottleneck (node k) as h changes. Table I depicts the simulation parameters of the proposed algorithm. As expected, we can see from Fig. 3 and Fig. 4 that by connecting new nodes, the transmission interval of the bottleneck increases, resulting in more delay and lesser throughput. This is because the bottleneck has to relay the traffic from all nodes in the subset to the main network and vice versa. Therefore with the increase of additional nodes, not only does the performance (transmission interval and throughput) of node k degrade, but it also reduces the available throughput of the nodes in the subset. This is also true for the variation of Exp which results in different levels of throughput degradation, as shown in Fig. 3. It is evident from the figure that for $Exp = 0$ the throughput degradation of node k is more severe than in other cases mainly because of the smaller hold-off time and larger contentions from competing nodes in the neighborhood.

Also note that initial $E[S_k^N]$ for the bottleneck should be chosen reasonably according to the number of its neigh-

TABLE I
SIMULATION PARAMETERS

Simulation parameters	Value
θ	165
ρ (64-QAM)	108
S_{MS}	1
ς	2
Γ	5
ν (64-QAM)	$10ms$

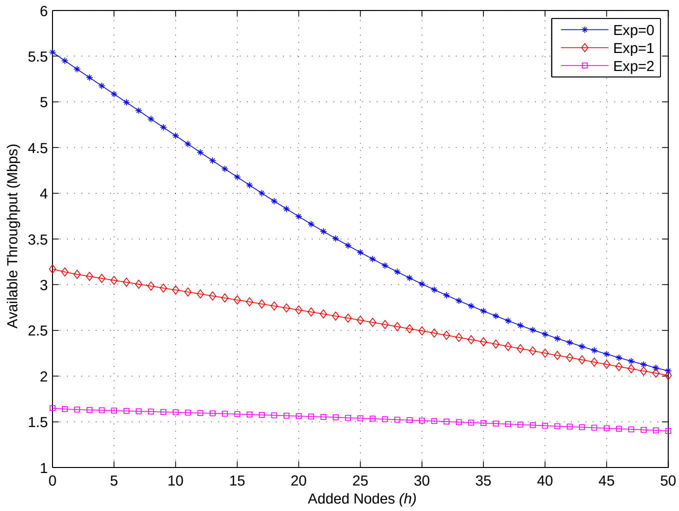

Fig. 3. Effect of different Exp on the achievable throughput of node k as h varies (using average initial $E[S^N k]$).

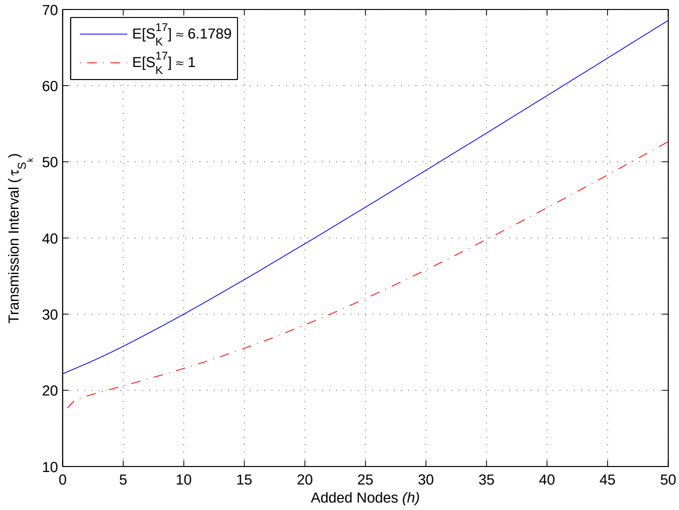

Fig. 4. Effect of bounded $E[S_k^N]$ on the transmission interval of node k as h varies ($Exp = 0$).

bors and the hold-off exponent value (Exp). It demonstrates the performance in the neighborhood where higher value denotes increased competing nodes. However results reveal that this value is bounded where the upper limit occurs (derived from (9)) when all nodes including node k itself have identical contention period (i.e., $E[S_k^N] = E[S_j^N]$). Obviously, increasing the number of N nodes results in larger contention period of each node and consequently larger upper bound. Here, $E[S_k^N] = E[S_j^N] \approx 6.1789$ is evaluated for a neighborhood size of $N = 17$. Conversely, the lower bound of transmission interval[1] depends on all nodes (excluding node k) in the neighborhood having very large $E[S_j^N]$ (alternatively, nodes are silent from large contentions in their corresponding neighborhood) which results in $E[S_k^N]$ becoming approximately unity. For such contention period (bounded $E[S_k^N]$) with $N = 17$, Fig. 4 illustrates the effect on node k as h varies. With different initial transmission intervals, the performance of node k will be bounded by this region. Table II shows the maximum bound (h^u) for different values on N nodes. As discussed above the upper bound of initial contention period can be derived from (9) for different values of N as shown in Table II. The selection of h^u (maximum achievable node subset) corresponds to the approximate initial choice of bounded $E[S_k^N]$ (bounded values) for different N, and guarantees a throughput of 2 Mbps (arbitrary choice) for each h nodes. This is also demonstrated in Fig. 5 which depicts the changes in individual node throughput as h^u varies ($N = 17$). For the benefit of the readers, Fig. 5 illustrates a magnification of a section bounded by x axis $= (15, 35)$ and y axis $= (0, 5)$. From this, we can see that for a node throughput of 2 Mbps, the value of h^u is given as 17 and 21 for $E[S_k^{N=17}] \approx 6.1789$ and $E[S_k^{N=17}] \approx 1$ respectively. In addition, note that the throughput degradation is significant for $h = 1$ to 5 when the node subset is small. However as h increases the degradation reduces mainly because of the lesser available throughput from node k and larger subset size, as follows from (15).

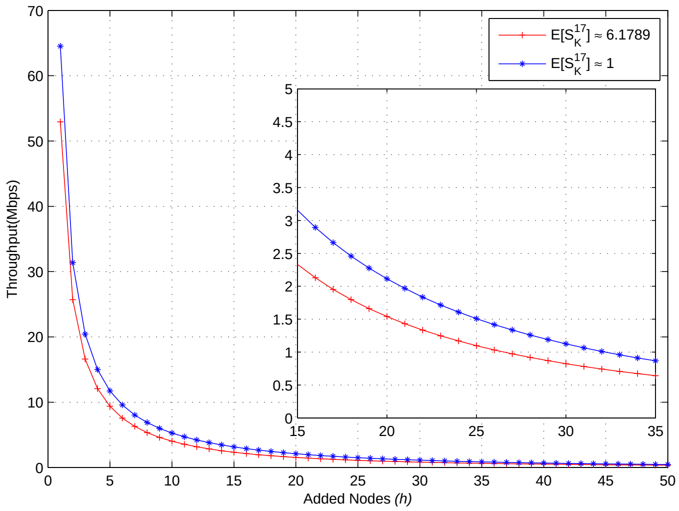

Fig. 5. Achievable throughput for each node in the subset for bounded initial $E[S^N k]$ as h varies ($Exp = 0$).

TABLE II

THE UPPER BOUND (h^u) OF NODE k WITH DIFFERENT N NODES.

initial $E\left[S_k^N\right]$ (lower bound, upper bound)	N	h^u
$\approx (1, 6.1789)$	17	$(21, 17)$
$\approx (1, 16.6954)$	30	$(18, 14)$
$\approx (1, 35.8149)$	50	$(16, 11)$
$\approx (1, 85.3474)$	100	$(11, 6)$
$\approx (1, 135.2202)$	150	$(10, 5)$

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[1] As per [8], when $N \leq 16$ (i.e., $E[S_k^N] \approx 1$) enough transmission opportunities are available and the contention can be neglected.

VI. CONCLUSIONS

In this paper, we have dimensioned a WMN using distributed scheduling to estimate the effect of performance variance of network extension on the bottleneck. For simplicity purposes, we have considered all nodes in the architecture to have identical hold-off time. The expression derived measures the capacity of the bottleneck in terms of transmission interval and available throughput. The paper also develops a method for selecting the maximum number of nodes (mesh routers/clients) that can be accommodated by the bottleneck without degrading the QoS of the neighbors. This provides a feasible mechanism for the network providers or operators in carrying out network extension as per their service requirements.

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