A Distributed Admission Control Scheme for Wireless Mesh Networks

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Abstract— **Admission control is a key management function in wireless networks, particularly Wireless Mesh Networks (WMNs), in order to support multimedia applications that require Quality of Service (QoS) guarantees. Even using state of the art schemes to provide QoS, if the amount of traffic in the network is allowed to increase in an uncontrolled manner, network performance will deteriorate significantly degrading the QoS for all network traffic. With admission control, a new flow is admitted only if the QoS requirements of all flows in the network still can be met after the new flow begins. This paper introduces a distributed admission control scheme, called RCAC (Routing on Cliques Admission Control) for WMNs. We propose an analytical model that enables computing the appropriate admission ratio to guarantee that the loss rate in the network does not exceed a target value; the model also allows computing end-to-end delay necessary to process flow requests with delay constraints. RCAC achieves scalability since it partitions the network into cliques; only clique heads are involved in the admission control procedure. Simulations, using ns-2, demonstrate that RCAC accepts new incoming flows only when the network target loss rate and end-to-end delay are satisfied and maintains relatively high resource utilization in a dynamic traffic load environment.**

Index Terms*— *Admission control, WMNs, Multi-channels, Quality of Service, stochastic.

I. INTRODUCTION

WMNs are becoming increasingly popular for providing connectivity among communities. They consist of two types of nodes: Mesh Clients (MCs: devices that require connectivity) and Mesh Routers (MRs: form the backbone of WMNs). Compared to Ad hoc networks, MRs in WMNs are usually stationary; for this reason, better performance is expected. However, supporting QoS in wireless networks, especially in WMNs, remains a big challenge. A lot of work has been done to improve the capacity and to maximize throughput in WMNs; examples of efficient schemes for routing, channel assignment and scheduling using multiple radios and channels can be found in [1, 2, 3]. However, when the network is overloaded, none of these schemes can prevent QoS degradation (e.g., huge data losses, longer delays). Thus, admission control schemes are necessary to provide QoS support; new traffic flows are accepted into the network only when there are sufficient available resources.

Stochastic models are widely used in the field of performance evaluation of wired networks. Compared to wired networks, the links in wireless networks, particularly WMNs, are inherently shared and difficult to isolate; this makes the performance of WMNs difficult to predict. Indeed, interferences among links cause performance degradation; it is fundamental to consider both local resources and resources at neighboring nodes when analyzing the performance [4,5].

In this paper, we propose a stochastic distributed admission control mechanism for WMNs called RCAC "Routing on Cliques Admission Control". RCAC accepts a new flow request only when there are enough available resources to carry the flow while satisfying predefined thresholds of loss rate and end-to-end delay (e.g., different values for different types of traffic). This will avoid situations in which uncontrolled resource usage leads to network breakdown (i.e., severe congestion). RCAC partitions the WMN into cliques (see Section III for definitions); only clique heads are involved in the admission control procedure; this makes RCAC scalable for large sized networks. Inside a clique, RCAC computes the available bandwidth while making use of local bandwidth information and neighboring bandwidth information; this is necessary to take care of interferences among 1 and 2 hops nodes. To the best of our knowledge RCAC is the first stochastic admission control mechanism for WMNs to consider two QoS parameters: packet loss and end-to-end delay; these two parameters determine network transmission quality in multi-channel and multi-radio WMNs. RCAC attempts to answer the following question: for a given WMN, can new flows be accepted into the network while keeping packet loss probability under the target packet loss probability and end-to-end delay under the target delay.

The paper is organized as follows: Section II briefly discusses related work in the field. Our notations, assumptions and network model are described in Section III. Section IV presents our proposed stochastic model. We present simulation results in Section V. Finally, Section VI concludes the paper.

II. RELATED WORK

The new challenges introduced by wireless networks, require more research and different perspectives to provide QoS management. The authors in [6] report that it is necessary to have a mechanism for admission control; however, they do not present any specific solution. In SWAN [7], the admission controller listens to all packet transmissions to collect information about bandwidth and congestion. It proceeds by sending probe messages; however, probing causes a lot of overhead and packet loss. In addition, SWAN does not consider the fact that two nodes could contend, for a channel, even without directly communicating. The authors in [4] propose Contention-Aware Admission Control Protocol (CACP) mechanism. CACP provides admission control for flows in a single-channel ad hoc network based on the knowledge of both local resources at a node and the effect of admitting new flows on neighboring nodes. The scheme in [5] is most closely related to CACP; it integrates admission control with ad hoc routing and channel reuse due to parallel transmissions for more accurate estimation of channel utilization. In [8], the authors propose a method that requires that each node measures both the occupied bandwidth and the average collision ratio; the measured value is compared to a given threshold; then, a decision to accept or not a new flow is made using a simple rule. The authors in [9] propose a strategy for admission control to provide QoS guarantees required by each class of traffic; the throughput and delay are estimated based on an analytical model with measured parameters for

Enhanced Distribution Coordination Function (EDCF) to decide whether traffic is to be accepted or not. In [10], Quality Access Point (QAP) measures the medium utilization and affirms the transmission opportunity budget (TOXP) through beacon signals for each access category (AC). If TOXP is consumed for one AC, the new flow could not gain transmission time and current flows could not increase their transmission time. In [11], Yuxia et al. propose an admission control algorithm for IEEE 802.11e; their model is based on the concept of conflict graph. The major problem with this model is that the utilization of the conflict graph is highly complex; even for a moderate-sized network, the number of interference constraints can be hundreds of thousands. The model works well in multi-hop single channel for a small-sized network; however, the approach is centralized which is not convenient for large networks.

In our proposed approach, we take into consideration the knowledge of both local and neighboring resources in distributed stochastic analytical model with two QoS parameters: delay and loss. We partition the networks into a set of cliques; only clique heads (CHs) are involved in the admission control procedure. We model interconnected CHs as a queuing network and we approximate packet loss probability with overflow probability in each clique; to this end, we estimate total packet arrival at time t in each clique. The objective of our proposal is to compute an admission ratio for a given packet loss probability. Indeed, for a target value of packet loss probability, we are able to determine the number of flows that can be accepted into the network while satisfying the target. Our proposal also takes end-to-end delay into account when processing new flow requests.

III. NETWORK MODEL

In this section, we propose a network model for WMNs and we illustrate how an equivalent queuing and stochastic network model can be constructed. But first, we define key concepts, namely connectivity graph and cliques, and present the assumptions/notations used in the rest of the paper.

A. *Connectivity Graph*

A WMN is represented by an undirected graph, called connectivity graph, $G=(V,E)$ where V represents the set of mesh nodes and E the set of edges between these nodes. $\forall (u,v)\in V$, an edge $e=(u,v)\in E$ if the distance between u and v, denoted $d(u,v)$, is smaller than the minimum range, denoted $\min(r_u,r_v)$, of u and v (i.e., $d(u,v)\le \min(r_u,r_v)$) where r_u and r_v represent the radio transmission ranges of nodes u and v respectively. Since we consider a multi-radio and multi-channel WMN, channel assignment is needed. The connectivity graph with channel assignment is denoted $G_A=(V,E,A_G)$ where $A_G=\{A_G(u),\forall u\in V\}$ and $A_G(u)$ is the set of channels assigned to u }. We denote NC the number of channels per node, and NR the number of radios per node; typically, we have $NR\le NC$.

Fig. 1 shows an example of connectivity graph G_A= (V = {A, B, C, D, E, F}, E = {(A, B)...(C, D)}, A_G = { $A_G(A)$, .., $A_G(F)$ }) in which we connect two nodes u and v if they share the same channel and the distance between them is smaller or equal to $\min(r_u,r_v)$. In this example, NR = 2 radios and each node is labeled with its channels assignment; for example, D, with 2 radios, is assigned channels 1 and 2 ($A_G(D)=\{1,2\}$). The radio transmission range of C and D is 200 m and 250 m respectively, the distance between C and D is smaller than $\min(200,250)$, and they share the channel 2; thus, the edge $(C,D)\in E$.

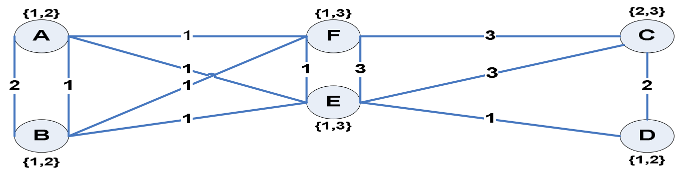

Fig. 1. Connectivity Graph: G_A

B. *Cliques*

A clique is represented by an undirected graph where for each two vertices/nodes, in the graph, there exists an edge connecting them; all the edges in the graph use the same channel. A maximal clique is a clique to which no more vertices can be added. We use maximal cliques to determine the nodes which compete to access the same channel. Therefore, two nodes i and j that belong to the same clique must not be active simultaneously. Our proposed admission control scheme takes into account both local and neighboring resources. Therefore, we define two types of maximal cliques (see Figures 2-3): (1) *A-clique* is defined as a set of nodes, A, sharing the same channel and having a pair wise distance smaller than or equal to the minimum radio transmission range of the pair nodes (i.e., $d(u\ ,v\ )\le \min(r_u,r_v),\forall u,v\in A$); and (2) *B-clique* is defined as a set of nodes, B, that use the same channel and have a pair wise distance in the interval $]\min(r_u,r_v),R]$ $\forall u,v\in B$ where R is the interference range; *B-cliques* are used to identify nodes in the Carrier Sense Range (CSR).

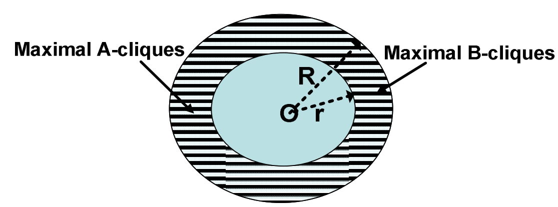

Fig. 2. Transmission and CSR intervals

Fig. 3 shows maximal cliques of type A and B computed using the connectivity graph shown in Fig. 1. For example q1/w=1 is an *A-clique* that is composed of 4 nodes {A, B, F, E}. All these nodes share the same channel 1. {A, D}/w=1 is a *B-clique*, where distance between nodes A and D is in $]\min(r_A,r_D),R]$ and they share the same channel 1.

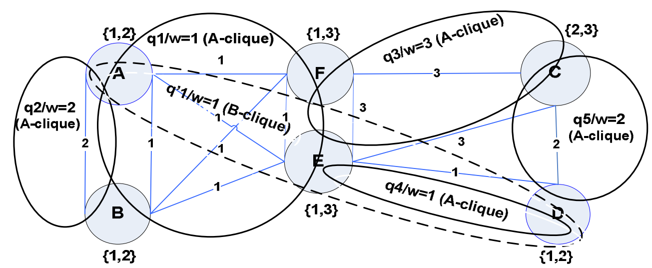

Fig. 3. *A-cliques* and *B-cliques*

Each *A-clique* is represented by its clique head (CH). In this paper, we use a simple algorithm that selects a node with the smallest degree as the CH; other algorithms can be used without any changes to our proposed admission control scheme. CHs are the only nodes involved in the admission control procedure; more specifically, they are responsible for computing admission ratio, available bandwidth, maximum occupancy and average service time of *A-cliques* they represent. The details of the election algorithms are illustrated in Table I.

TABLE I. CH ELECTION ALGORITHM

Input:
- *A-cliques*
- Degree of each node (the degree of node X is X_degree) /* the degree of node u is equal to the number of *A-cliques* to which u belongs*/

Output:
- *A-cliques* with nodes that are either *ordinary* or CH /* a node is either *ordinary* or a *clique head (CH)**/

Variables:
- X is a node in the *A-clique*
- CH : Clique Head

Initialization:
- **X.state=** *ordinary* /* for each node */

Begin
- X sends request_to_be_CH /* All nodes in the *A-clique* receive the request*/
- _X.state=CH
- Upon receipt of a request, a node Y performs the following:

If Y_degree < X_degree
Then Y sends request_to_be_CH (Y_degree)
Y.state=CH
Else
Y.state=*ordinary*
End if

End

In the rest of the paper *A-clique* and CH will be used interchangeably.

C. Assumptions/Notations

The assumptions considered throughout this paper are: (1) Each *A-clique* experiences a different load and may have a different capacity than other A-cliques; (2) New flows arriving in each *A-clique* are uniform, independent and Poisson distributed; (3) All the information exchanges and the admission ratio computation happen only once at the beginning of each control period of length *T*; (4) Routers are synchronous; (5) The assignment of channels is static; and (6) Network failures (link/node) are not considered. In this paper, we consider the notations shown in Table II.

TABLE II. LIST OF SYMBOLS/PARAMETERS

V	The set of nodes (routers) in the network
Clique	Every vertex is adjacent to every other
Maximal clique q_i	The clique which does not belong to any other larger clique: (*A-clique* / *B-clique)*
Q_A	The total number of *A-cliques*
CH_i	Clique Head of *A-clique* q_i
C_i	Available bandwidth of *A-clique* q_i
$N_i(t)$	Number of active flows at time *t* in *A-clique* q_i
N_{ct}	Set of *A-cliques* that can contend for channel *k* utilization, $k \in \{1..NC\}$
θ_k	Bandwidth of k^{th} channel
NC	Number of channels per radio; channels are identified/numbered from 1 to *NC*
NR	Number of radios per node
MO_i	Maximum occupancy in *A-clique* q_i
T	Length of the control period
$PA_i(t)$	Packet arrival rate at time *t* in *A-clique* q_i
$Loss_i(t)$	Packet loss probability at time *t* in *A-clique* q_i
a_i	New flow admission ratio in *A-clique* q_i
R_i	New flow rejection ratio in *A-clique* q_i
b_i	Average service time of CH_i
D	End-to-end delay
m_i	New flow request arrival rate in *A-clique* q_i
$E[X]$	The mean of variable *X*
$A_i(t)$	Number of flows that are active in *A-clique* q_i at $X*T$, where $X*T \le t \prec (X+1)*T$ and X is an Integer, minus the number of flows that terminate during $]X*T,t]$
$New_i(t)$	Number of flows that have been generated or started transiting *A-clique* q_i during $]X*T,t]$ where $X*T \le t \prec (X+1)*T$ and X is an Integer
$Left_i(t)$	Number of flows in *A-clique* q_i that terminate during $]X*T,t]$ where $X*T \le t \prec (X+1)*T$ and X is an Integer,
P_{loss}	Target packet loss probability
$\Delta_{category}$	Target end-to-end delay
r_v	Radio transmission range for node v. $\forall u \in V$, if *u* is in the r_v of node *v*, *u* and *v* are neighbors
R	Interference range
CSR	Carrier Sensing Range $]\min(r_u, r_v), R]$,$\forall u, v \in V$ if *u* is in the CSR of node *v*, *u* and *v* may interfere
C_neighbors	$\forall u, v \in V$, if *u* is in the CSR of node *v*, *u* and *v* *are* C_neighbors
$D^{(u)}_{\text{degree}}$	Node degree (number of *A-cliques* to which node u belongs)

D. Queuing model

The network consists of V routers, Q_A *A-cliques*, Q_B *B-cliques*. All two-hop neighbors transmitting on the same channel are interfering neighbors. Each node may be a source and a destination of packets. We assume that packet size is L (see Section IV.A for more details about the traffic model in use) and that a client may transfer a packet to its mesh router as soon as it is generated. Therefore, the delay between the generation of a packet and its transfer to the mesh router is negligible. Each mesh router is assumed to have (physical) finite buffers. Each CH is assumed to have (logical) finite buffers too. In our approach, we model logical buffers in each *A-clique* at each CH. The packets are served by the CHs in First-Come First-Serve (FCFS) manner. We propose to model WMNs as a queuing network (see Fig. 4). The stations/nodes of the queuing network represent the CHs.

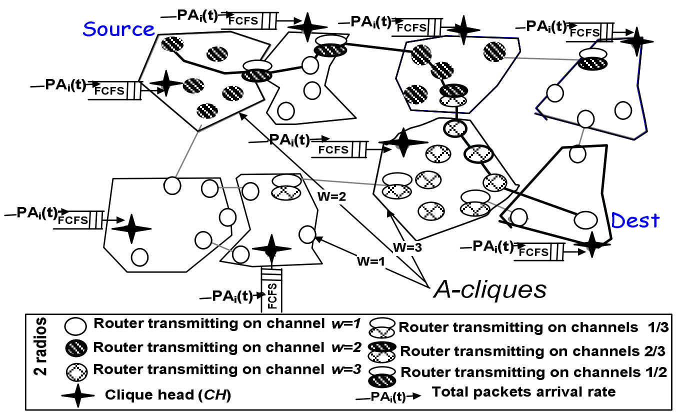

Fig. 4. WMN represented as queuing network

1) Contention Matrix

The contention matrix is equivalent to the connectivity graph (see Section III.A). It shows nodes which are grouped in the same *A-clique* and only one of these nodes can be active at any given time. Let us define the contention matrix C for all channels as:

$$C_q^u = \begin{cases} w, & \text{if node } u \in A\text{–clique } q \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

The dimension of matrix C is $Q_A \times V$.

Let us now define the contention matrix for channels set *NC* as:

$$C_q^u = \sum_{w=1}^{NC} wC^w, \qquad w \in \{1..NC\} \tag{2}$$

where C^w defines the unit matrix related to a given channel w.

2) Node Degree

The degree of node u is defined as the number of *A-cliques* that the node u belongs to using the same or different channels. To compute the degree, we have to sum the lines in the matrix represented in Equation (2) for each channel w.

$$For\ u \in V, \quad D_{\text{degree}}^{(u)} = \sum_{w=1}^{NC} \sum_{i=1}^{Q_A} C_{i,u}^w \tag{3}$$

Fig. 3 shows that the degree of node E is 3, because E belongs to three *A-cliques* q1/w=1, q3/w=3, and q4/w=1.

3) Maximum occupancy

We assume that bandwidth requirements of incoming flows are multiple of F. For example, if F is equal to 100 Kb and the bandwidth requirement B_{req} of flow j is 1 Mb, then B_{req} is 10F.

The maximum occupancy MO_i, of *A-clique* q_i is equal to the number of (unit) flows that can be accepted/supported by q_i .

$$MO_i = \frac{C_i}{F} = X \tag{4}$$

where C_i represents the minimum available bandwidth of all nodes belonging to *A-clique* q_i .

If more than MO_i flows exist in *A-clique* q_i , then q_i is overloaded. In this case, the probability of packets loss is very high. Our proposed scheme, RCAC, rejects flows when *A-cliques* are overloaded or packet loss probability is higher than P_{loss} . Thus, the first step in RCAC is to evaluate the maximum occupancy in each *A-clique* so that the bandwidth requirement B_{req} does not exceed the available resources within *A-clique*. Since each node has different channel views, the maximum occupancy is not simply a local concept. To demonstrate this relationship, we illustrate a scenario with six stations (Y, D, X, D1, Z, and D2) as shown in Fig. 5. The MAC layer protocol is IEEE 802.11 with radio transmission ranges of 150 m for Y, 250 m for X, 200m for Z, and R=550m. The Bandwidth of the wireless channel θ1 is 2 Mbps. X and Z are C_neighbors. Y is X's neighbor and is out of Z's CSR. Thus, we can conclude that *A-clique* q_1 and q_2 are C_neighbors.

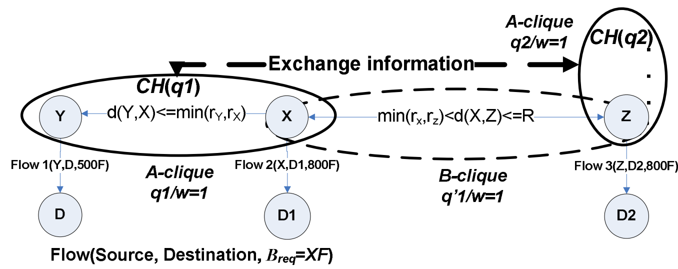

Fig. 5. Traffic Scenario: an Example

TABLE III. CHANGES OF LOCAL MAXIMUM OCCUPANCY

At time $t=t_0$, MO in q1,q2	Y (MO_{q1}=2000)	X (MO_{q1}=2000)	Z (MO_{q2}=2000)
Flow*1* starts	(MO_{q1}=1500)	(MO_{q1}=1500)	(MO_{q2}=2000)
Flow2 starts	(MO_{q1}=700)	(MO_{q1}=700)	(MO_{q2}=1200)
Flow*3* starts	(MO_{q1}=700)	*congested*	(MO_{q2}=400)

Table III shows the values of *MO* of the different cliques as computed by Y, X, and Z. When flow1 starts transmitting, only local information (*MO* of q_1) is used; however, when flow2 starts transmitting, not only local *MO* is used but also neighboring *MO* (of q_2) since (1) X belongs to *B-clique*, and (2) X and Z are C_neighbors; thus, *MO*s of both *A-cliques* are reduced. If flow3 starts transmitting, congestion will occur (Table III); to avoid this congestion, one has to check the availability of resources in both q_1 and q_2 before accepting flow3. In our proposed scheme, we make use of Equation (5) to compute the maximum occupancy of node *i*.

$$MO_i = \min(MO_i(local), MO_j(local), ..., MO_k(local)) \tag{5}$$

where *j*, .., *k* are C-neighbors of *i*.

For the example shown in Fig. 5, the maximum occupancy of Z (after accepting flow 1 and flow 2 in the network) is $MO_i(Z) = \min(1200, 700) = 700$; since flow3 requires 800, Z will simply reject it when using RCAC.

IV. PROPOSED STOCHASTIC MODEL

A. Traffic characterization

We denote the packet generating process of an individual flow k as S_k , and we assume that individual packet generating processes are independent and identically distributed random variables with the mean $E[S]$. Thus, the total packet arrival rate $PA_i(t)$ in an *A-clique* q_i at time t, is expressed as

$$PA_i(t) = \sum_{k=1}^{N_i(t)} S_k \quad (6)$$

where $N_i(t)$ denotes the number of active flows at time t in *A-clique* q_i. To characterize $PA_i(t)$ by a Poisson distribution, we need to specify the parameter of $PA_i(t)$, namely the mean. Using the moment generating functions of random processes $PA_i(t)$ and S_k, we obtain Equation (7) (see [12] for details).

$$E[PA_i(t)] = E[N_i(t)]\, E[S] \quad (7)$$

The number of active flows in *A-clique* q_i at time t can be expressed by the summation of the number of active flows $A_i(t)$ and new flows $new_i(t)$ (see Table II):

$$N_i(t) = A_i(t) + New_i(t) \quad (8)$$

Therefore, in order to compute $E[PA_i(t)]$, first we have to compute $E[S]$. Since $E[S]$ is known a priori, we need only to compute $E[N_i(t)]$ (see next Section for details).

B. Computing the admission ratio

The admission ratio a_i is computed as follows:

- Compute the mean, E[S], of the packet generating process of all flows in the *A-clique*.
- Approximate the total packet arrival process by a Poisson distribution.
- Compute the packet loss probability in each *A-clique* q_i.

Our choice of Poisson distribution is due to the fact that it is most commonly used for analysis purposes. Such type of traffic behavior is expected when the network is accessed by high number of voice/video/data traffic users.

The tail of the Poisson distribution is used to find $Loss_i(t)$ (see Equation 9). For that aim, we approximate the packet loss probability by the overflow in each *A-clique*. Therefore, we approximate the network overflow by the overflow at each single *A-clique*.

$$Loss_i(t) = \Pr obability\,\{PA_i(t) \rangle C_i\}$$

$$Loss_i(t) = \sum_{k=C_i+1}^{\infty} e^{-\lambda t} \frac{\lambda t^k}{k!} = 1 - \sum_{k=0}^{C_i} e^{-\lambda t} \frac{\lambda t^k}{k!} \quad (9)$$

$$\lambda = E[PA_i(t)] = E[N_i(t)]\, E[S], \quad (10)$$

where the mean number of active flows in *A-clique* q_i at time t is given by: $E[N_i(t)] = E[A_i(t)] + E[new_i(t)]]$

It is worth noting that both incoming (i.e., starting) and outgoing (i.e., terminating) flows are modeled as Poisson distributions (Equation 11).

$$E[A_i(t)] = N_i(x*T) - E[left_i(t)] \quad (11)$$

where $X*T \le t \prec (X+1)*T$ and X is an Integer

In Equation 12, we express traffic generated by local *A-clique* q_i and transient traffic from adjacent *A-cliques*.

$$E[new_i(t)] = M_i \times \begin{bmatrix} a_1 m_1 \\ \vdots \\ a_i m_i \\ \vdots \\ a_{Q_A} m_{Q_A} \end{bmatrix} \quad (12)$$

where M_i is the i^{th} row of the following matrix *M*.

$$M = \begin{bmatrix} 1 & P_{q_1 q_2} & \cdots & P_{q_1 q_{Q_A}} \\ P_{q_2 q_1} & 1 & \cdots & P_{q_2 q_{Q_A}} \\ \vdots & \vdots & \ddots & \vdots \\ P_{q_{Q_A} q_1} & \cdots & \cdots & 1 \end{bmatrix} \quad (13)$$

The dimension of the matrix *M* is $Q_A \times Q_A$, and it represents the proportions of the traffic generated in one *A-clique* that is routed through another, where Q_A is the total number of *A-cliques*. The value of a cell M_{ij} is equal to 1 if i=j, and equal to $P_{q_i q_j}$ if i≠j, where $P_{q_i q_j}$ consists of the fraction of the traffic generated in *A-clique* q_i that is routed through *A-clique* q_j. To compute $P_{q_i q_j}$, we propose to use a heuristic, called Ford-Fulkerson-based Matrix Computation (FFMC).

FFMC takes as input the amount of traffic generated by each *A-clique*, the capacities of the links connecting the *A-cliques*, source *A-cliques* (i.e., *A-cliques* that generate traffic), and one destination; if there is only one gateway in the network, then the destination is that gateway; otherwise, the destination is a virtual node to which all gateways are connected. First, FFMC executes (multi-source) Ford-Fulkerson algorithm (which computes the maximum flow in a network [13]) on the input to compute the amount of traffic which passes through each of the links connecting the *A-cliques*. Second, it selects an *A-clique*, from the set of *A-cliques*, which does receive no traffic from direct neighbors; we make the assumption that there is at least one *A-clique* that will be selected. Then, it computes the row for the selected *A-clique* in the matrix M using the output of the Ford Fulkerson algorithm; FFMC fills the matrix using normalized values of the output of the algorithm. At the i^{th} step, we subtract the flows originating from *A-clique* corresponding to rows that have already been filled, and we apply the same procedure for the rest of *A-cliques*. Table IV presents the pseudo-code of FFMC.

TABLE IV. FFMC: PSEUDO-CODE

Input:

- *G*=(*S*, *E*) where *S* represents the set of *A-cliques*, represented by their CHs, and *E* the set of edges between *A-cliques*; the value/cost $e_{q_j q_k}$ associated with an edge connecting 2 cliques (q_j,q_k) is equal to the bandwidth between them.
- S_{q_i} : Amount of traffic S_{q_i} generated in *A-clique* q_i

Output:

- M: Traffic proportions matrix between *A-cliques*

Variables :

- q_i : *A-clique from S*
- *C* : is a set of *A-cliques*
- *G':=*(*S, E'*)
- *t:* real
- *Result: A-Clique*

Initialization :

- C:={∅}
- *Result:=Null*
- $Mq_iq_j = \begin{cases} 0 \ if \ \ i \neq j, i \ and \ \ j \in \{1..Q_A\} \\ 1, \ otherwise \end{cases}$

Begin

1. G':= Execute_Ford_Fulkerson_algorithm(G) /* the value/cost $e'_{q_jq_k}$ associated with an edge (q_j,q_k) (belonging to E') connecting 2 cliques q_j and q_k is equal to the fraction of traffic generated in q_j and going to q_k. */

2. **REPEAT**

2.1 Randomly select q_i from S such that q_i has no traffic coming from its neighbors

2.2 $S := S - \{q_i\}$

2.3 $C := C \cup \{q_i\}$

2.4 **REPEAT**

2.4.1 Result:=Choose an *A-clique* q in $\overline{C}$ such that all of its incoming traffic comes from *A-cliques* in C and $q' \in C$ and there is a flow from q' to q

/* If an *A-clique* is not found, Result is equal to Null */

2.4.2 **If** (Result**!=Null**) **then**

2.4.2.1 $P_{q_iq} := P_{q_iq} + t_{q'q} \times P_{q_iq'}$ where t is the fraction of traffic generated in q' and going to q

/*($t := \dfrac{e'_{q'q}}{\sum All \ outgoing \ \ traffic \ from \ \ q'}$)*/

2.4.2.2 $C := C \cup \{q\}$

Endif

UNTIL all *A-cliques* are in C **or** Result = Null

2.5 **For** every q_j and q_k in G' **Do**

2.5.1 $e'_{q_jq_k} := e'_{q_jq_k} - S_{q_i} \times P_{q_iq_j} t q_j q_k$ /*subtract all the traffic originating from q_i from the traffic of the graph G'*/

2.6 C:={∅}

UNTIL S={∅}

End

For better understanding of the operation of FFMC, let us consider the example shown in Fig. 6. Fig. 6-(a) shows the graph G characterized by four *A-cliques*: three source *A-cliques* and one destination *A-clique* (i.e., gateway); more specifically, G=({q0,q1,q2,q3}, { $e_{q_0q_1}$ =2, $e_{q_0q_2}$ =4, $e_{q_1q_3}$ =3, $e_{q_2q_1}$ =3, $e_{q_2q_3}$ =2}) and S_q = { S_{q_0}, S_{q_1}, S_{q_2} }={1.2, 0.8, 1}. FFMC executes The Ford-Fulkerson Algorithm taking G as input and produces as output G'=({q0,q1,q2,q3}, { $e'_{q_0q_1}$ =1.2 × 40%, $e'_{q_0q_2}$ =1.2 × 60%, $e'_{q_2q_1}$ =1.2 × 20%, $e'_{q_2q_3}$ =1.2 × 40%+1 × 100%, $e'_{q_1q_3}$ =1.2 × 40%+0.8 × 100%}), in which the edges represent the fraction of traffic $e'_{q_jq_k}$ generated in q_j and going to q_k. For instance 1.2 × 40% is the fraction of traffic $e'_{q_0q_1}$ generated in q_0 and going to q_1. Fig. 6-(b) shows how we compute the row for the selected *A-clique* q_0 in the matrix M using the output of the Ford Fulkerson algorithm. Hence, in Fig. 6-(c), we subtract the flows originating from *A-clique* q_0 (row 0 in matrix M of Fig. 6-(b)) from the traffic of the graph G'. After executing step 2.5 in FFMC algorithm, $e'_{q_0q_2}$ becomes equal to 0. The next step, consists of applying iteratively the same process (as shown in Fig. 6-(b) and Fig. 6-(c)) for the rest of *A-cliques* until S is empty (S=∅). At the end, FFMC obtains the traffic proportions matrix M among all *A-cliques* (see Fig. 6-(d)).

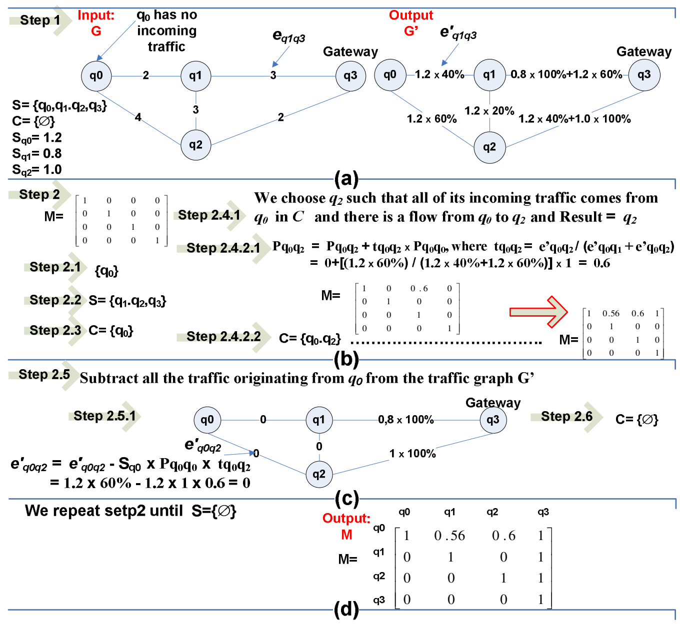

Fig. 6. Example of the FFMC operation

Therefore, the admission ratio a_i for each *A-clique* q_i can be found by solving Equation (14) where the only unknown parameter is a_i , and where P_{Loss} is the target packet loss probability.

$$Loss_i(t) < P_{Loss} \tag{14}$$

C. Computing delay in each A-clique

In this section, we present the delay analysis of the WMN model described in section III.B. Let N_{ct} denotes the number of C_neighbors *A-cliques* of q_i identified by *B-cliques*. Before transmitting a packet each node counts a random timer which is exponentially distributed with mean Backoff duration $\frac{1}{\xi}$ [14].

The average service time of q_i is expressed as follows:

$$b_i = \frac{1}{\xi} + \frac{L}{\theta_{channel}} + INTER_i \tag{15}$$

In the case of no interference,

$$INTER_i = 0 \,, \tag{16}$$

If interference exists, we consider that all interfering *A-cliques* have the same probability to access the medium. In this case,

$$INTER_i = \frac{L}{\theta_{channel}} \times \left(\frac{\sum_{k \in N_{ct}} PA_k \; C_k}{\sum_{k \in (N_{ct} \cup i)} PA_k \; C_k} \right), \qquad (17)$$

The end-to-end delay for each path is determined by computing delay at each intermediate CH as follows:

$$D = \sum_{i \in PATH} b_i \qquad (18)$$

The delay parameter is the second QoS metric considered in our model. Before admitting a flow, RCAC checks whether the delay of the selected route is smaller than the target delay ($\Delta_{category}$) a priori fixed according to different type of video/audio/ftp traffic. This constraint is expressed as follows:

$$D = \sum_{i \in PATH} b_i < \Delta_{category} \qquad (19)$$

D. *Admission Control Using A-Clique Head*

RCAC is implemented by CHs. Each time a (source or transit) CH receives a new flow request, it checks whether (a) there is sufficient bandwidth to accommodate the flow while satisfying the target loss probability (by computing MO_i (Eq. 4)) and a_i (Eq. 14)); and (b) the delay of the path from the source to it is smaller than the target delay (by computing b_i (Eq. 16) and D (Eq. 19)). If the response is yes (i.e., it can accommodate the request), it forwards the request to the next CH towards the destination; otherwise, it sends a reject towards the source CH. Upon receipt of the request, the destination CH checks whether it can accommodate the request. If the response is yes, it sends an acceptation towards the source CH; otherwise, it sends a reject. More details about the inter-signaling protocol between CHs including concurrent processing of flow requests are not included in this paper because of limited space. Table V shows the pseudo-code of the proposed admission control algorithm executed by a CH, upon receipt of a flow request, in the path from the source CH to the destination CH. Different routing protocols can be used to determine a path, in terms of *A-cliques* (CHs), between a source and destination. In this paper, we used a modified version of AODV [15].

TABLE V. ADMISSION CONTROL ALGORITHM

Input:

- flow request(S, D, $B_{required}$) in q_j /* S: source; D: destination, $B_{required}$: required bandwidth*/

Output:

- Admission decision: acceptation or reject

Begin

- **Compute** local MO_j (Eq. 5)
- **Exchange** information with C_neighboring cliques about MO to compute new MO_j (Eq. 6)
- **Compute** a_j (Eq. 15) and b_j (Eq. 17)
- **Check** the delay from the source to this q_j whether it is smaller than the target delay (Eq. 20)

If Random (0, 1) < a_j && $N_j(t) < MO_j$

    If D is in qj **Then**

        return (**acceptation**)

    Else Forward to the next hop towards D

    Endif

  Else return **(reject)**

  Endif

End

V. ANALYSIS AND SIMULATIONS

To evaluate the effectiveness of our distributed admission control model (RCAC), we perform simulation experiments using ns-2 [15]. In the simulation, stations (routers/gateways) are randomly distributed in a 1000m x 1000m coverage area. The radio transmission range r takes one of the following values: 150m, 200m and 250m and the transmission interference R of each wireless station is 550m. We examine the performance of the proposed admission control scheme on a random topology. Real-time traffic flows arrive at each wireless station as Poisson distribution. E[S] is equal to 20packets/s. We consider target packet loss probability P_{loss} equal to 0.05 (i.e., 5%) and target delay $\Delta_{category}$ equal to 35 ms. Thus, the objective is to accept new flows only when the loss rate (resp. delay) does not exceed 5% (resp. 35 ms). The simulations will show how "accurate" RCAC ("analytical vs. simulations") in deciding to accept or reject new flows.

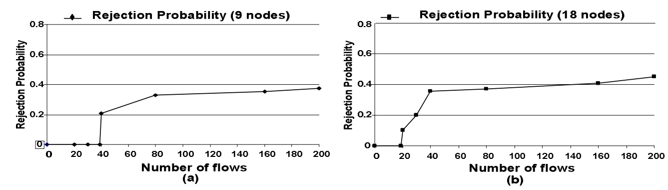

Fig. 7. Flow Rejection Probability

In Fig. 7 the X-axis indicates the number of flows and the Y-axis indicates the probability of rejected flows in the network. Rejected probability is expressed as follows:

$$PR_i = \frac{\sum_{i=1}^{Q_A} m_i R_i}{\sum_{i=1}^{Q_A} m_i} \qquad (20)$$

where $R_i = 1 - a_i$ and m_i is the new flow arrival rate in an *A-clique* q_i .

More specifically, Fig. 7-(a) and Fig. 7-(b) show the distribution of the total number of requests as well as the rejection request probability using RCAC. In the case of 9-nodes network, RCAC starts rejecting flows starting from the 40th flow while in the case of 18-nodes network, RCAC starts rejecting flows starting from the 20th flow. This can be explained by the fact that in the case of 18 nodes, interferences are more present than in the case of 9 nodes (we use the same geographic area size and random topologies); furthermore, we use manual (ad-hoc) channel assignment; thus, different results may be produced using different channel assignment schemes (e.g., optimal schemes).

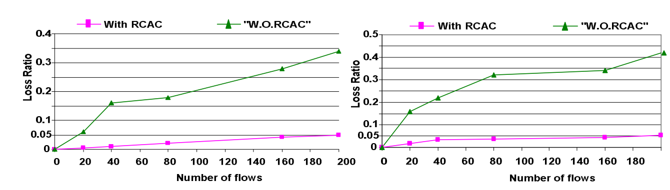

Fig. 8. Loss rate with and without RCAC

Fig. 8-(a) shows the variation of the loss rate with the number of flows in a network of 9 nodes when using W.O.RCAC and RCAC. W.O.RCAC corresponds to the basic scheme that always accepts and routes flows from sources to destinations using AODV [16]. Figure 8-(a) shows that even when the traffic increases, the loss rate does not exceed 5% when using RCAC; however, with W.O.RCAC the loss rate target is exceeded when the number of flows in the network approaches 20. The packet loss rate is more than 16 times bigger with W.O.RCAC than with RCAC when the number of flows in the network approaches 40; up to this point, RCAC did not start rejecting flows. When RCAC starts rejecting flows, the loss rate increases rapidly to more than 7 times (in the case of 200 flows) the packet loss target. Figure 8-(b) shows the results for 18-nodes network; RCAC does not exceed the packet loss target while W.O.RCAC violates the target starting from flow 6. For example, when the number of flows approaches 20, the packet loss rate is more than 9 times bigger with W.O.RCAC than with RCAC.

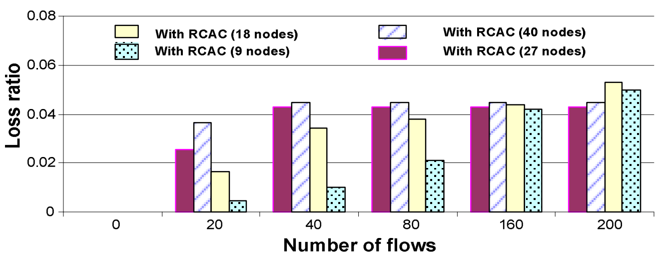

Fig. 9. Loss rate versus number of flows

Fig. 9 shows the loss rate variation versus the number of flows in networks with 9, 18, 27 and 40 nodes respectively. We observe that when the traffic load and the network size increase, RCAC maintains a loss rate under the target of 0.05. These results confirm our claim of controlling the loss rate in the network.

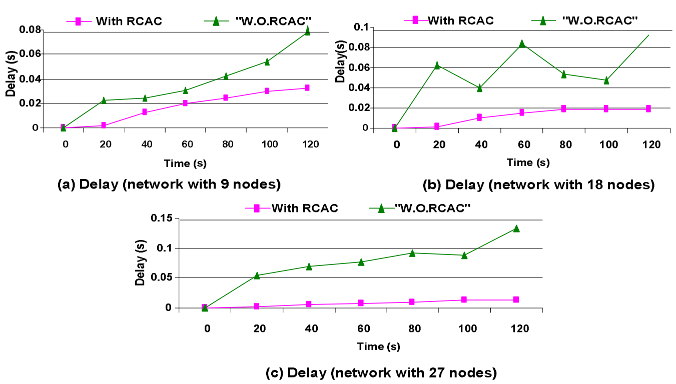

Fig. 10. Delay variation with and without RCAC

The delay performance over time is shown in Fig. 10. Fig. 10-(a) shows the variation of the delay in a network of 9 nodes when using W.O.RCAC and RCAC. With RCAC, the delay of all the admitted flows does not exceed 35 ms, however, with W.O.RCAC, the delay increases significantly starting from 20s; it exceeds 35 ms at 65 s. Fig. 10-(b) shows the results for 18-nodes network; RCAC does not exceed the delay target while W.O.RCAC exceeds the target starting from 10s.

In Fig. 10-(c), when RCAC starts rejecting flows starting from 10s; the delay exceeds the target delay starting from 17 s with W.O.RCAC. It is noteworthy that all the admitted real-time flows have a delay below 16 ms when using RCAC As the number of nodes increases, we have more paths and much more less treatment assigned to each *CH*. This impacts positively the delay in the network.

It is worth noting that a number of simulation results (e.g., including throughput for different traffic classes, such as ftp, voice and video, delay vs. number of flows, etc.) are not included because of lack of space. However, all the simulations (included or not in the paper) validate the characteristics of RCAC in terms of controlling the packet loss rate and end-to-end delay in WMNs.

VI. Conclusion

We presented a stochastic distributed admission control scheme based on cliques (RCAC) to support real-time services in WMNs. Simulations confirm the ability of RCAC to guarantee a loss rate in the network that does not exceed a predefined target loss rate. Currently, we are investigating the impact and an adaptation of RCAC in case of failures and dynamic channel assignation.

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