Load Dependent Resource Allocation in Cooperative Multiservice Wireless Networks: Throughput and Delay Analysis

Thomas Lagkas
Department of Informatics and Telecommunications Engineering
University of Western Macedonia
Kozani, Greece
tlagkas@ieee.org

Dimitrios G. Stratogiannis, Georgios I. Tsiropoulos
School of Electrical and Computer Engineering
National Technical University of Athens
Athens, Greece
dstratog@mail.ntua.gr, gitsirop@mail.ntua.gr

Panagiotis Sarigiannidis, Malamati Louta
Department of Informatics and Telecommunications Engineering
University of Western Macedonia
Kozani, Greece
psarigiannidis@uowm.gr, louta@uowm.gr

***Abstract*--Cooperative wireless networks supporting multiple services necessitate the application of a robust bandwidth allocation policy to ensure Quality of Service (QoS) provision to different applications. In this work, a load dependent bandwidth allocation technique is presented considering traffic priority and buffer load in the relay nodes of a cooperative communication network. An analytical approach for bandwidth sharing is provided along with a delay analysis, verifying that the proposed scheme can efficiently provide traffic differentiation, satisfying, also, the QoS requirements in terms of bandwidth, packet transmission rate and delay. The results obtained by the analysis are validated via simulations, confirming the improved network performance in terms of throughput and delay.**

Buffer load; delay; MAC; QoS; Simulation; Cooperative wireless network

I. INTRODUCTION

Cooperative communications are based on the improvement of the performance of a wireless network achieved by the cooperation among different nodes and the adoption of spatial diversity [1, 2]. The cooperation among nodes of a wireless communication system leads to improved system capacity, optimal spectrum use and increase of system reliability, since bit error rate and outage probabilities are decreased [1, 3]. In a cooperative relay communication system, each node transmits each own data and collaborates with other relay nodes, accepting and forwarding appropriately packets received towards a destination node. Data packets arriving from other nodes are queued in the relay buffers of each node. The overall system throughput increases, while aggravating queuing delay at the relay nodes gives rise to higher end-to-end transmission time [4]. Thus, buffer traffic load in the cooperative nodes has a critical impact on the network performance parameters such as throughput, delay and jitter.

Data packets of different applications require distinct treatment by the network according to their Quality of Service (QoS) characteristics and their priority. For example, critical emergency communications data calls should be favoured during the resource allocation process, satisfying their QoS requirements. In this perspective, multiple services support in a cooperative wireless network should involve the development of an efficient resource allocation scheme in conjunction with a prioritization mechanism for handling different traffic types. Appropriate techniques providing access and efficient medium sharing are mandatory.

In recent literature, various Medium Access Control (MAC) protocols for cooperative networks have been presented. In [5], the CoopMac protocol has been introduced based on a set of new characteristics applied on the data and control plane of the well known IEEE 802.11 MAC protocol. In [6], the relay enabled Distributed Coordination Function (rDCF) has been presented, which is based on the accessibility of the relay nodes to forward data packets of other nodes. Furthermore, a new protocol called Cooperative MAC (CMAC) has been proposed in [3]. CMAC exploits the spatial diversity of cooperative communications through a retransmission technique of partially correct frames that are combined to reconstruct the initial one. The above protocols are variants of the IEEE 802.11 MAC protocol, which has certain performance limitations in terms of bandwidth sharing when applied to cooperative networks.

In this paper, a load dependent bandwidth allocation technique is presented, considering buffer load in the nodes of a cooperative communication network that overcomes the constraints of existing protocols. The presented technique is based on traffic differentiation according to its priority and it can be considered as part of a Medium Access Control (MAC) protocol. The main objective of this technique is to provide enhanced QoS support, taking into account various parameters such as packet priorities, throughput and delay. Moreover, an analytical approach is provided to examine the impact of buffer load on bandwidth sharing along with a packet delay analysis considering a cooperative communications scenario.

The rest of the paper is organised as follows. In Section II, the load dependent bandwidth allocation technique considering traffic priorities is studied. The simulator developed to validate the proposed technique is described in Section III. In Section IV, the simulation results and the evaluation of the proposed technique are discussed. Finally, conclusions are drawn in Section V.

II. Load Dependent Bandwidth Allocation Scheme

A. Bandwidth Allocation Scheme

A cooperative wireless communication system is considered where different nodes may either generate new data or receive and forward relay data packets transmitted by other nodes. Data traffic is categorized based on its priority and every node has a different packet buffer for each traffic priority level supported, as defined in IEEE 802.11e standard [7]. The objective of the proposed technique is to prioritize data packets according to the QoS requirements of the applications supported, while network resources are assigned to nodes proportionally to their load. Specifically, the designed scheme allocates resources to the packet buffers of each node proportionally to their load and traffic priority. The total bandwidth allocated to a node is equal to the sum of the resources allocated to its buffers.

Let N denote the number of buffers in a single node. The traffic load status of ith buffer is described by the quantity $Q_i(t)$, which depends on the buffer priority and its load at a given time t. That is

$$Q_i(t) = z^{p_i} L_i(t)\,, \tag{1}$$

where $i \in \{1,...,N\}$, $z \geq 1$ is a preset priority factor given by the ratio of the bandwidth allocated to a buffer divided by the bandwidth assigned to a buffer with equal load having the consecutive lower priority, $p_i \in \mathbb{Z}^*$ is the priority of ith buffer and $L_i(t)$ denotes the actual load of ith buffer at a given time t.

The normalized portion of bandwidth allocated to each buffer is denoted by $normQ_i(t)$, given by the following equation:

$$normQ_i(t) = Q_i(t) \Big/ \sum_{k=1}^{N} Q_k(t)\,. \tag{2}$$

Each node can be characterized by the sum of $Q_i(t)$ values of all buffers within the node. Resource allocation within each node is based on $normQ_i(t)$, while the bandwidth allocated to ith buffer depends on the $Q_i(t)$ value.

B. Packet Transmission Rate Analysis

Based on the sharing technique presented above, bandwidth is allocated to each buffer of every node taking into account its load and traffic priority. As previously mentioned, for a specific node, data packets are either generated from the node under consideration or arrive from other nodes to be forwarded to a destination node. Despite the fact that Packet Generation Rate (*PGR)* and bandwidth allocation might be given, as shown in (1) and (2), respectively, the channel access probability cannot be determined directly since the allocation is affected by the traffic flow priority. Consequently, to provide the requested QoS levels for the traffic flows supported, appropriate modifications to the priority levels or the bandwidth sharing policy are necessary.

Suppose that there are two buffers ($N=2$) corresponding to different traffic flows with discrete priority levels. Given that $f_i(t)$, $i = \{1,2\}$, is the total number of bits transmitted at time t by the buffer i, the respective Packet Transmission Rate (*PTR*) is represented by its first derivative, $f_i'(t)$. In the presented analysis, it is assumed that there is a bandwidth capacity constraint where the buffers *PGR* is greater than the available bandwidth b, otherwise, the *PTR* of each buffer will be equal to the *PGR*, which is the ideal case. In what follows, the node buffers *PTR*, c, is obtained by

$$\frac{f_1'(t)}{f_2'(t)} = c \xrightarrow{f_1'(t)+f_2'(t)=b} f_1'(t) = c(b - f_1'(t)) \longrightarrow$$

$$f_1'(t) = \frac{cb}{1+c} \xrightarrow{(1),(2)} \frac{z^{p_1} L_1(t)}{z^{p_1} L_1(t) + z^{p_2} L_2(t)} b = \frac{cb}{1+c} \longrightarrow$$

$$z^{p_1} L_1(t) = c z^{p_2} L_2(t)\,. \tag{3}$$

Without loss of generality, it is assumed that the *PGR* of each buffer remains constant in time, therefore its mean a_i can be used, e.g., the packet generation process follows the Poisson distribution and its rate *PGR* is equal to the expected mean value λ. Let $G_i(t)$ denote the total load expressed as the number of bits that have arrived to the ith buffer during the observation interval $[0, t]$. Evidently, the first derivative of $G_i(t)$ is equal to a_i. Since a_i is constant, $G_i(t)$ is a linear function of t. Moreover, the first derivative of $f_i(t)$ is also constant in time, therefore $f_i(t)$ is also a linear function of t. In this course, c can be obtained as follows

$$(3)\xrightarrow{G_i(t)-f_i(t)=L_i(t)} z^{p_1-p_2}(G_1(t)-f_1(t)) = c(G_2(t)-f_2(t))$$

$$\xrightarrow{G_i'(t)=a_i} z^{p_1-p_2}(a_1 t - f_1'(t)t) = c(a_2 t - f_2'(t)t)$$

$$\xrightarrow{p_1-p_2=r} z^r\left(a_1 - \frac{cb}{1+c}\right) = c\left(a_2 - \left(b - \frac{cb}{1+c}\right)\right) \longrightarrow$$

$$a_2 c^2 + (a_2 - b - a_1 z^r + bz^r)c - a_1 z^r = 0 . \qquad (4)$$

Solving the equation (4), c can be calculated by the following quadratic formula

$$c = \frac{-(a_2 - b - a_1 z^r + bz^r) \pm \sqrt{(a_2 - b - a_1 z^r + bz^r)^2 + 4a_1 a_2 z^r}}{2a_2} , \qquad (5)$$

considering only the value of c such that $c \geq 0$, since the *PTR* cannot be negative.

Following a general concept, suppose that multiple buffers are employed by each node. It is considered that traffic flows are categorized and grouped based on their priority to different priority levels that correspond to virtual buffers. The analysis of the proposed load dependent approach for resource allocation considering multiple virtual buffers can become quite complex. In this case, the *PTR* of each buffer can be calculated via solving a system of equations that is derived accordingly. The notations for the general case employed are given below

- V denotes the number of virtual buffers, where $V \leq N$,
- $f_r'(t)$ is the *PTR* of the *r*th virtual packet buffer, $r = \{i, j\}$, $i, j \in \{1, ..., V\}$, which is equal to the bandwidth allocated to it,
- b_{ij} denotes the aggregated bandwidth assigned to *i* and *j* buffers with $i \neq j$ and
- $c\left[b_{ij}\right] = f_i'(t) / f_j'(t)$ is the *PTRs* ratio, determined by (5).

In what follows, an indicative case of multiple buffers has been selected to demonstrate the features of the load dependent allocation technique. Assume that there are three virtual buffers $N = 3$ and the total available bandwidth capacity is b . Consequently, the following system of equations is formed

$$f_1'(t) = \frac{c[b_{12}]b_{12}}{1 + c[b_{12}]} , \qquad (6)$$

$$f_2'(t) = \frac{c[b_{23}]b_{23}}{1 + c[b_{23}]} , \qquad (7)$$

$$b_{12} = f_1'(t) + f_2'(t) , \qquad (8)$$

$$b_{23} = f_2'(t) + f_3'(t) , \qquad (9)$$

$$f_1'(t) = b - f_2'(t) - f_3'(t) . \qquad (10)$$

By solving the above system the $f_1'(t)$, $f_2'(t)$, $f_3'(t)$ and the aggregated bandwidth assigned to buffers b_{12} and b_{23} are obtained.

Note that in the presented approach buffers are assumed to have infinite capacity. However, a more realistic approach where buffers of limited capacity are considered should also be examined. The constraint of limited buffer capacity will result into two cases. In the first one, the buffer reaches its maximum capacity, since it is assigned less bandwidth than the *PGR*, while in the second one the bandwidth assigned is adequate to serve its *PGR*, therefore, its load remains constant. To determine which of the two cases occurs the following algorithm is employed:

Algorithm for finite capacity buffers

- Step A: The algorithm estimates the available bandwidth W_i for *i*th buffer as follows

$$W_i = \frac{z^{p_i} C_i}{\sum_{k=1}^{N} C_k} b , \qquad (11)$$

  where, C_i is its maximum capacity.
- Step B: If $W_i \geq a_i$, then the *PTR* of *i*th buffer is set equal to a_i and the algorithm proceeds to the next step. Otherwise, the algorithm returns to Step A and the next buffer is examined until all the buffers are assigned with *PTR* equal to a_i or none of the remaining buffers satisfies the condition of Step B.
- Step C: The *PTR* of *i*th queue as obtained during the previous steps is subtracted from the total available bandwidth. The process is repeated for the remaining buffers taking into account each time the remaining unallocated bandwidth.
- Obviously, if at least one buffer gets less bandwidth than the required by its *PGR*, then all the buffers will get full. In this case, the *PTR* of each buffer is determined proportionally to the W_i .

C. Delay Analysis

One of the most important network performance metrics is the delay within the buffer of a cooperative node since it is a critical QoS parameter for various applications. The proposed bandwidth allocation technique ensures that the delay in the relay node is compliant with the QoS requirements of the traffic flow. Since the mean transmission rate of each traffic flow can be determined, it is feasible to estimate the average corresponding delay. According to Little's law [8], the average system queue size equals the jobs' arrival rate multiplied by the average waiting time. In the case of a cooperative network, the average system queue size is equivalent to the average buffer load, the job's arrival rate corresponds to the mean generation rate and the average

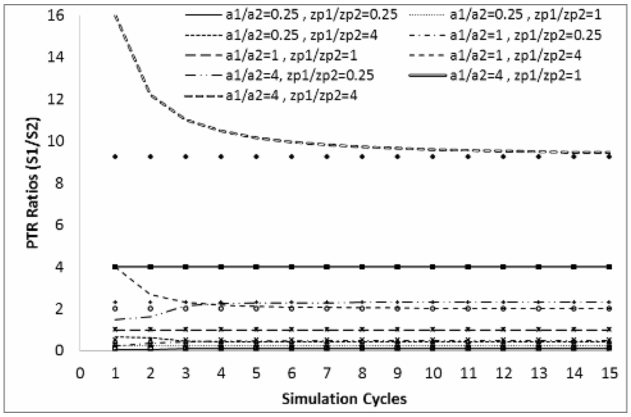

Figure 1. Convergence of the *PTR*s ratio provided by the simulation to the ratio determined by the analysis.

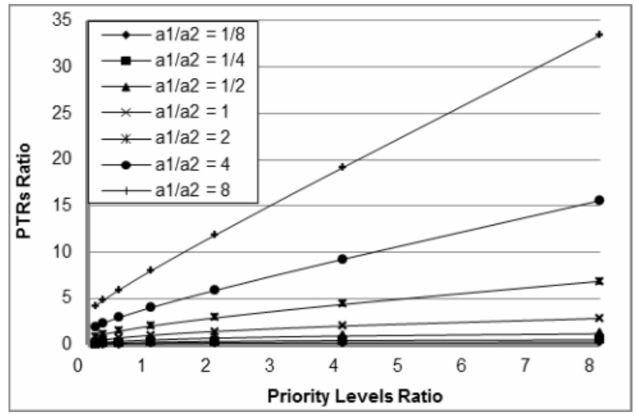

Figure 2. Two flows *PTRs* ratio versus priority levels ratio for various *PGRs* ratios.

waiting time is equal to the average delay (d). Hence, for flow i it holds

$$d_i = \frac{1}{\tau}\int_0^{\tau} L_i(t)dt = \frac{1}{\tau}\int_0^{\tau} (G_i(t) - f_i(t))dt = \\ = \frac{1}{\tau}\int_0^{\tau} (a_i t - f_i^{'}(t)t)dt = \frac{(PGR - PTR)\tau}{2}. \quad (12)$$

III. Model Validation and Analysis

To validate the proposed resource allocation technique an appropriate simulator has been developed in C#. In the performed simulations two priority levels have been considered. The actual *PTR* of ith buffer and the total number of bits transmitted considering all buffers are denoted by Si and b, respectively. The number of bits entering the first or the second buffer is denoted by $a1$ and $a2$, respectively. The simulator operation is implemented via consecutive allocation cycles as follows.

Simulation Loop for Bandwidth Allocation

```
do
  {
   L1 += a1;
   L2 += a2;
   Q1 = Math.Pow( z, p1 ) * L1;
   Q2 = Math.Pow( z, p2 ) * L2;
   normQ1 = Q1 / (Q1 + Q2);
   normQ2 = Q2 / (Q1 + Q2);
   S1 = normQ1 * b;
   S2 = normQ2 * b;
   if ( S1 > L1 )
    {
     S1 = L1;
     S2 = b - S1;
     if ( S2 > L2 )
      S2 = L2;
    }
   else if ( S2 > L2 )
    {
     S2 = L2;
     S1 = b - S2;
     if ( S1 > L1 )
      S1 = L1;
    }
   L1 -= S1;
   L2 -= S2;
} while <TERMINATION CONDITION>
```

The accuracy of the analysis presented is validated by the convergence of the simulation results to the analytical ones, as demonstrated in Fig. 1 for the *PTR*s ratio. Illustrative numerical examples for variable number of operation cycles are presented using different values for the ratio $a1/a2$ and priority levels ratio z^{p1}/z^{p2}. The values of the network parameters employed are: $b = 1000$, $a2 = 1000$, $z = 2$ and $p2 = 4$. Note that the continuous lines correspond to the simulation results, while dots are assigned to the results obtained by the analytical formulas provided in Section II. As demonstrated in Fig. 1, the *PTR*s ratio obtained by simulations has a slight divergence from the numerical results, when a low number of simulation cycles is performed. However, when the number of cycles increases, an excellent agreement between both results is observed.

IV. Numerical Results and Discussion

Numerical results for two cooperative network scenarios are presented in this section, employing the proposed bandwidth allocation technique. The examined cooperative network involves source nodes which communicate with an out of range destination node through intermediate relay nodes. A traffic flow of different priority and rate is generated from each source node and their packets are buffered in the respective relay nodes before their transmission to the destination. The respective packet buffers are considered to have infinite capacity, which is a common assumption when analyzing related queuing schemes [9]. The presented evaluation scenario examines the resource allocation among the relay nodes when they share a common medium to communicate with the destination node.

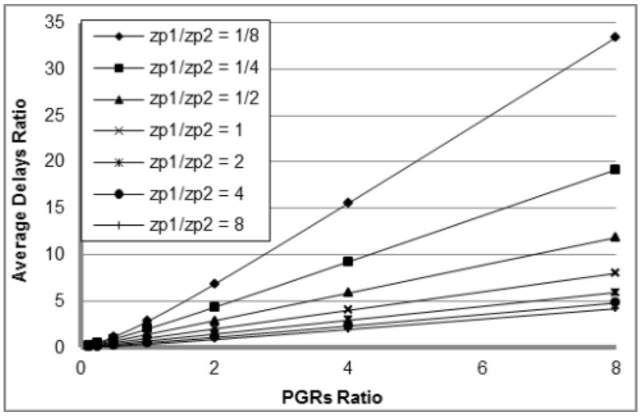

Figure 3. Two flows average delay ratio versus *PGRs* ratio for various priority levels ratios.

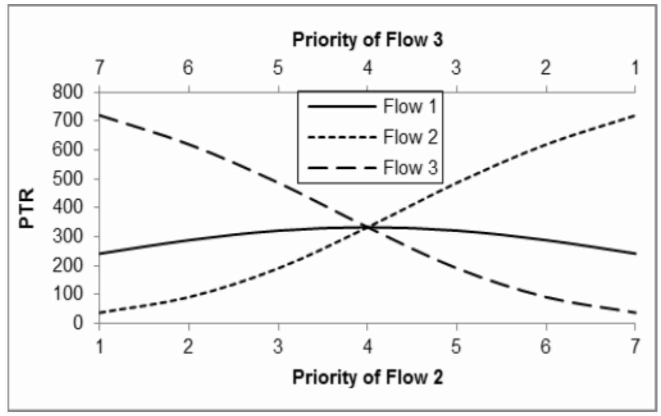

Figure 4. Three flows *PTR* versus varying combination of flow 2 and flow 3 priorities.

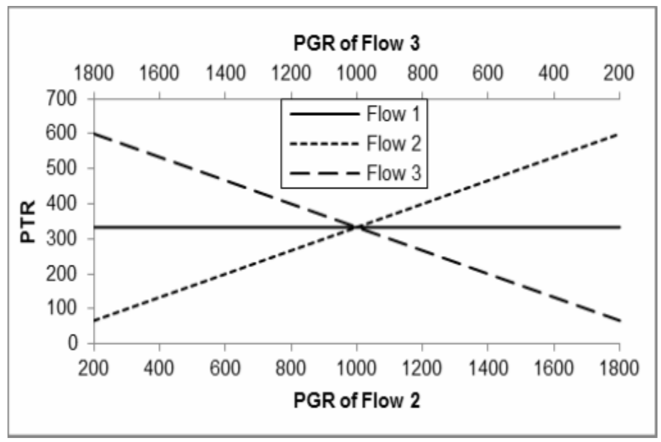

Figure 5. Three flows *PTR* versus varying combination of flow 2 and flow 3 *PGRs*.

A. Two Relay Node Scenario

The first scenario includes two source nodes, two relay nodes and a common destination node. In Fig. 2, the two relay nodes *PTR*s ratio is plotted with respect to their priority levels ratio, for different *PGR*s ratios. It is evident that priority levels ratio correspond to also higher values of the *PTR*s ratio. Specifically, the rate of this increment rises for higher *PGR*s ratio values.

The results regarding packet delay are depicted in Fig. 3, where the impact of the two nodes *PGRs* ratio on their average delay ratio for various priority levels ratio values is considered. The average delay was calculated based on the delay analysis provided in Subsection II.C. From Fig. 3 it is observed that the average delay ratio increases with the *PGRs* ratio. However, higher values of the priority levels ratio correspond to lower values of the delay ratio.

B. Three Relay Node Scenario

The second cooperative network scenario under consideration includes three source nodes, three relay nodes and one common destination node. The respective performance results regarding three different traffic flows with different priorities originating from different nodes are depicted in Fig. 4 and Fig. 5. These results are obtained via solving the equation set related to the multi-buffer analysis presented in Subsection II.B. The solution of the corresponding system of five equations was derived employing the *fsolve* function of MATLAB, which is a variant of the Powell trust-region dogleg method described in [10].

In Fig. 4, the *PTR* for the three traffic flows is plotted as a function of the second flow priority and the third flow priority. The priority of the first flow is considered fixed at value 4, while all flows are characterized by the same *PGR* value. It should be clarified that traffic priorities assigned to different flows are independent each another. However, in Fig. 4 and Fig. 5 fixed priority combinations are considered for sake of results comparison. In Fig. 4, the flow priority increases with respect to the other flow priorities. Moreover, greater flow priority values correspond to also greater *PTR* values for the specific traffic flow. Specifically, from Fig. 4 it can be observed that the dependence of *PTR* on traffic flow priority is non-linear.

Fig. 5 depicts the three flows *PTR* values for different *PGR* values and the same priority level. Following the same concept regarding the presented results, the *PGR* of the first flow is fixed at 1000, while a fixed combination of the second and third flows *PGRs* is considered. It is observed that *PTR* increases proportionally to *PGR*, as already expected, when the traffic flows considered are of the same priority level.

V. CONCLUSION

In this paper a load dependent bandwidth allocation technique is proposed. The presented technique takes into account the traffic QoS requirements, such as its priority level and the *PGRs*. The results obtained demonstrate that the proposed technique can provide traffic differentiation and efficient resource allocation along with minimum delay. Numerical and simulation results were presented to validate the proposed model. The flexibility of the proposed technique indicates than it can be easily adapted as a part of MAC protocol for cooperative wireless networks providing QoS guarantees.

REFERENCES

[1] [1]Y.-W. Hong, W. J. Huang, F.-H. Chiu and C.-C.J. Kuo, "Cooperative communications in resource-constrained wireless networks," IEEE Signal Process Mag., vol. 24, no. 3, pp. 47-57, May 2007.

[2] A. Nosratinia and A. Hedayat, "Cooperative communication in wireless networks," *IEEE Commun. Mag*, vol. 42, no. 10, pp. 74-80, Oct. 2004.

[3] S. Shankar, C.-T. Chou and M. Ghosh, "Cooperative communication MAC (CMAC) – A new MAC protocol for next generation wireless LANs," in Proc. *International Conference on Wireless Networks, Communications and Mobile Computing*, vol. 1, 2005, 1-6.

[4] G. Bansal, V. Sharma, N.B. Mehta and E. Altman, "Relay load balancing in queued cooperative wireless networks with rateless codes," in Proc. *ICC*, 2010, pp. 1-6.

[5] P. Liu, Z. Tao, S. Narayannan, T. Korakis and S. Panwar, "CoopMAC: A cooperative MAC protocol for wireless LANs," *IEEE J. Sel. Areas Commun.*, vol. 25, no. 2, pp. 340 – 354, Feb. 2007.

[6] H. Zhu and G. Cao, "rDCF: A relay-enabled medium access control protocol for wireless ad-hoc networks," *IEEE Trans on Mob. Comput.*, vol. 5, no. 9, pp. 1201-1214, Sep. 2006.

[7] IEEE Std 802.11e-2005, "IEEE Standard for Information Technology--Telecommunications and Information Exchange Between Systems--LAN/MAN Specific Requirements--Part 11 Wireless Medium Access Control and Physical Layer specifications, Amendment 8: Medium Access Control Quality of Service Enhancements," 2005.

[8] J. D. C. Little, "A proof for the queuing formula: L= λ w," *Operations Research*, vol. 9, no. 3, pp. 383-387, 1961.

[9] A. K. Sadek, K. J. R. Liu, and A. Ephremides, "Cooperative Multiple Access for Wireless Networks: Protocols Design and Stability Analysis," in Proc. *40th Annual Conference on Information Sciences and Systems*, 2006, pp. 1224-1229.

[10] M. J. D. Powell, A Fortran Subroutine for Solving Systems of Nonlinear Algebraic Equations, Numerical Methods for Nonlinear Algebraic Equations, P. Rabinowitz, ed., Ch.7, 1970.