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Mathematic Models for Quality of Service Purposes in Ad Hoc Networks

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1. Introduction

The quality of service, according to a networking context, is the degree of users' satisfaction of services that a communication system provides. It aims at improving communication behaviour under a correct data transmission and an optimal use of resources. According to this concept, quality of service is typically the performance criteria that evaluate the service provided.

Wireless multi-hop networks, including ad hoc networks, with their complex nature impose many constraints than in wired networks. Besides, the quality of service concerns the behaviour of the network, and is dealt with from different points of view. It typically addresses a set of metrics relevant to delay, bandwidth, jitter, packet loss rate, energy consumption, stability, security, and so on. It is worth noting, accordingly, that some criteria are very difficult to discern and can be still considered challenging. In this regard, security is not sufficiently addressed in a QoS context in ad hoc networking studies.

Inside the ad hoc networking field, the quality of service issues concern different layers on the network architecture. We distinguish between too main optics of quality of service studies: QoS models and QoS routing. A QoS model defines all mechanisms that the network should respect in order to guarantee the quality of service on the network. The model is based on and characterizes the architecture of the network. It includes all protocols that organize communication and connectivity between the different layers or components. In this respect, QoS routing presents a critical component in the model and a rich field for algorithm development. QoS routing consists of finding the best path to relay a source to a destination and guarantee the quality of service in parallel. In a general case, QoS routing consists to define metrics (usually one) that control the decision making to choose a path. The metrics nature affects the mathematical model and then the algorithm approach used to solve the problem of finding the best path.

Mathematical modelling of quality of service in ad hoc networking aims at improving the decision making on networks in an operational meaningful way. It addresses many concerns of the QoS and allows to benefit from various modalities and techniques of optimization theory.

This work reviews and discusses several mathematical models developed for or oriented to quality of service in ad hoc networks, and highlights the different forms that a model may take. Because we believe that several metrics of quality of service in ad hoc networks are in contradiction and thus the multicriteria optimization gives more opportunities in decision making and in reflecting the realistic system; we opt for multicriteria formulations in all our studies of QoS in ad hoc networks. In this regard, we present and analyze the contributions of such studies on improving ad hoc networks' behaviour.

2. Quality of service issues and ad hoc networks challenges

The quality of service presents a rich field for study in ad hoc networking until *the Internet QoS protocols cannot be migrated to the wireless environment* (Sarkar et al., 2007) and in general because of the difficulty to support all communication patterns that are usual in wired networks. The quality of service concerns the behaviour of the network, and is dealt with from different points of view. Furthermore, it refers to different notions at different networking layers (Sinha, 2005). We distinguish between two main optics of quality of service studies: QoS models and QoS routing. QoS models are architectures providing all mechanisms which governs some properties as time, scheduling and reliability (Brahma, 2006). Several models have been developed in the literature with different intentions, as FQMM (Xiao et al., 2000), SWAN (Ahn et al., 2002), INSIGNIA (Lee et al., 2000), dRSVP (Mirhakkak et al., 2000), etc. They are based on or a hybridization of the classical models, namely, InteServ and DiffServ which have proved their limits in ad hoc network environment[1]. As for QoS routing, it consists to find the route relaying source and destination and insuring the quality of service in parallel. Many issues are considered recently giving more areas of research in QoS concerns.

Essentially, quality of service concerns four topics in the current studies, namely, QoS models, QoS resource reservation, QoS routing, and medium access control protocol. However, from a mathematical point of view, QoS presents an economic problem which consists to optimize an objective cost under several constraints imposed by the network nature and proprieties. In this connection, quality of service typically addresses a set of metrics relevant to delay, bandwidth, jitter, packet loss rate, energy consumption, stability, security, and so on.

QoS in ad hoc networks contends with several vulnerabilities of the networks nature, as contention, waiting, and intrusion phenomena (see Fig. 1). Each one of these vulnerabilities may present a field of study in the context of QoS in ad hoc networking. Indeed, investigating intrusion in ad hoc networks may improve the connectivity which gives more guarantee of the QoS in this field.

In the same respect, contention may present a wide area in QoS studies in particular in the resource allocation strategies. Indeed, the wireless channel is shared by nodes with the same neighborhood. As shown in Fig. 1, node L gets into competition with the node D which receives both signals coming from node S (data source) and node L (noise source).

3. Mathematical QoS models

A mathematical model is a virtual maquette which represents a concrete phenomenon with mathematical symbols and semantics. In other words, it consists to describe the real-world phenomena by using scientific conceptions. Each modelling process starts with a question that can be investigated in order to describe, explain and predict the evaluation of a phenomenon. The nature of this question defers according to the approach adopted to study the phenomenon. Therefore, mathematical models are considered inside a set of mathematical fields or contexts, as operations researcher, control theory, automatic engineering, etc.

[1] IntServ model (Integration of Service) poses a problem of high volume of flow treatment and signalization, as for DiffServ model (Differentiation of Service), it requires a static topology and a network core with high bandwidth.

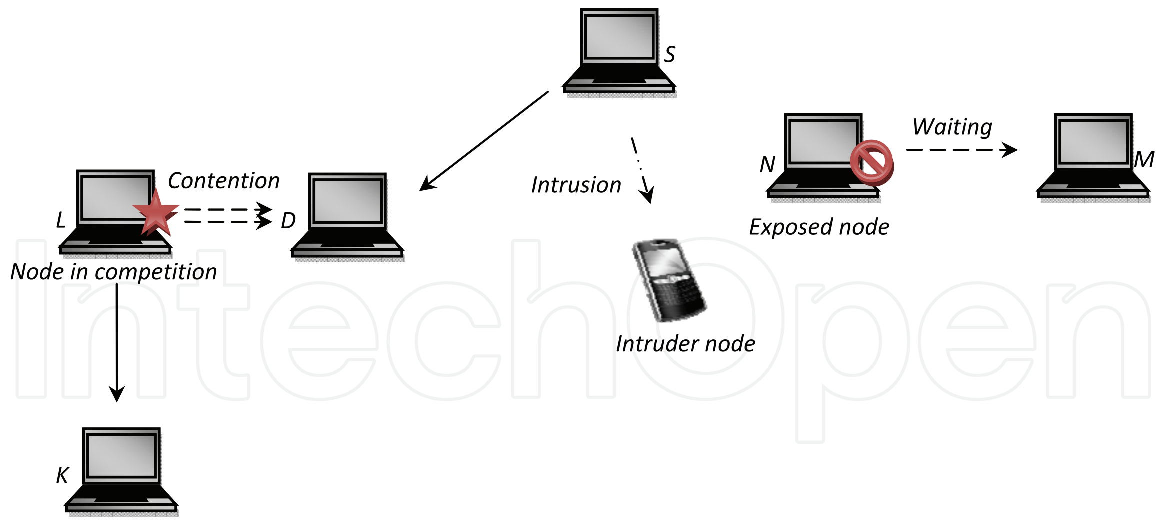


Fig. 1. Ad hoc networks challenges: contention, waiting, and intrusion phenomena (Amine, 2008).

Furthermore, the mathematical models differ according to the objectives and the constraints considered in the formulation. In a general case, the modelling process is described in Fig. 2.
Mathematical modelling of quality of service in ad hoc networking aims at improving the decision making on networks in an operational meaningful way. A mathematical modelling consists of determining objective-functions (criteria), which reflect the cost of communication in the network, as well as the constraints which limit the decision domain. In this context, metrics of QoS are considered as objective functions, and services, network proprieties and topology requirement are considered as constraints. Various studies were developed in the literature which follow this methodology with various modalities of modelling and optimization.
In networking science, protocols are defined as all mechanisms which govern the network behaviour in term of communication, transmission, routing, resource allocation, and so on. In this connection, a routing protocol deals with three issues, namely, the routes discovery, routes maintenance and data transmission. We distinguish according to the first issue two categories of protocols: Topology based and spatial position based (Amine, 2008). Besides, all protocols should respect free loop, sleep period considerations, security, and so on. From a mathematical point of view, protocols investigation should focus on the decision phase which takes place, evidently, before the transmission data process.
QoS routing consists of finding the best path to relay a source to a destination and guarantee the quality of service in parallel. It represents an advanced concept of best effort routing previously developed in ad hoc networking. In a general case, QoS routing consists to define metrics (usually one) that control the decision making to choose a path. The metrics nature affects the mathematical model and then the algorithm approach used to solve the problem of finding the best path.
Ad hoc networks are usually represented as a weighted directed complete graph $G(V, A)$ where V represents the set of vertices associated with the nodes of the network and A the set of edges representing all the possible communication links; i.e. $A = \{(i, j)/i, j \in V, i \neq j\}$. The aim of studying QoS is, in general, to determine an optimal path according to well defined objectives; subject to a set of well defined constraints that characterize the nature of the network.

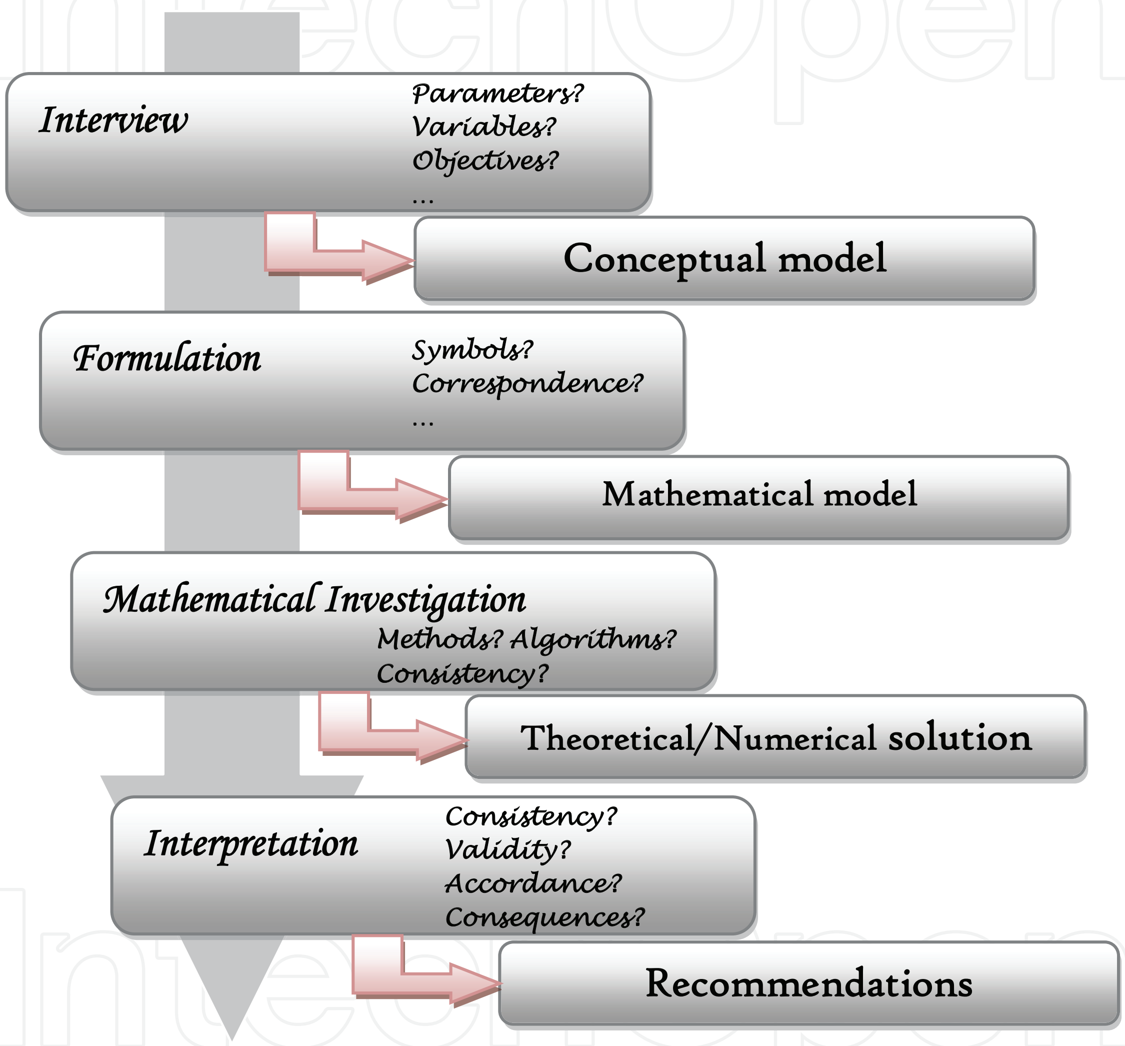


Fig. 2. Modelling process: a technical target leading from a phenomenon observation to a scientific result.

Let $\mathcal{P}$ stand for routing path from a source s of data (massage) to a destination d . We introduce the decision variable x defined as

$$x_{ij} = \begin{cases} 1 & \text{if } (i,j) \in \mathcal{P} \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

The transmission model usually adopted in ad hoc networking is defined as

$$p_{ij} = d_{ij}^{\alpha} \tag{2}$$

where p_{ij} is the energy per bit required to reach j from i and d_{ij} is the distance from i to j . α is an environment-dependent coefficient typically between 2 and 5 (Hashemi et al., 2007). The transmission energy is well considered to be symmetric, i.e.

$$p_{ij} = p_{ji} \quad ; \quad \forall (i,j) \in A \tag{3}$$

4. Multicriteria approaches: overview and contributions

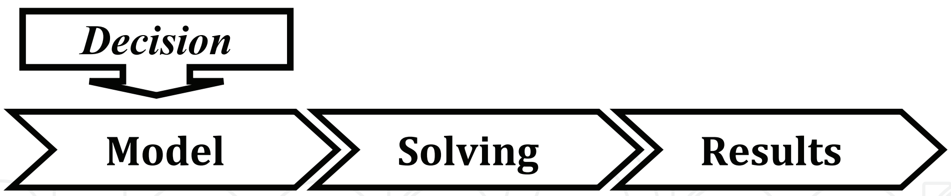
A multicriteria approach consists of taking into account all objective costs (criteria) that reflect the conceptual system problematic[2]. The consistency of a multicriteria model, takes from the contradiction between objectives functions; the optimization of a criterion affects the others. Thus, the optimization of all criteria cannot be done separately.
A mathematical multicriteria model can be represented in a general case as

$$\begin{cases} \min\left(f_1(x), f_2(x), \dots, f_m(x)\right) \\ \text{Subject to} \\ \quad h_i(x) = 0 \quad , \quad i = 1, \dots, k \\ \quad k_i(x) \leq 0 \quad , \quad i = 1, \dots, l \\ \quad\quad x \in \mathcal{D} \subset I\!R^n \end{cases}$$

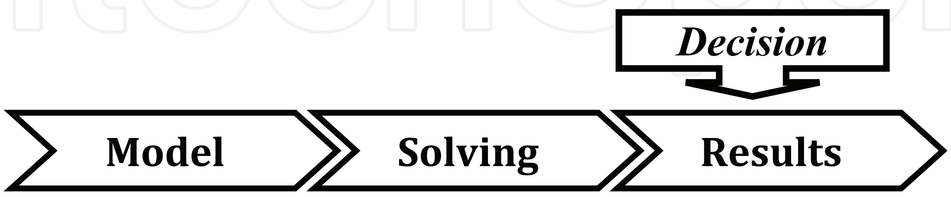
where $f_i : I\!R^n \to I\!R$, $i = 1, \dots, m$ are the objective functions, h_i and k_i are equality and inequality constraints respectively, and $\mathcal{D}$ is the domain in which the functions f_i are defined. The multicriteria optimization consists of finding the best compromise between all functions. This compromise is actually a set of solutions that are nondominated[3] by any feasible (realizable) solution. This set of all optimal solutions (in nondominance sense) is called *Pareto Front*.
Because quality of service refers at the first stage to the users' satisfaction, QoS strategies should give more choices at different ways. Besides, multicriteria optimization provides all alternatives representing optimal solutions according to different preference structures. In this, each alternative/solution is called *best* or *efficient* solution. Despite goal programming, aggregation methods, and scalarisation process which provide one solution. Multicriteria optimization involves providing all solutions representing the best compromise between all considered criteria.
The difference between monocriteria and multicriteria approach lies in time of decision making. Indeed, the monocriteria formulation consists of making decision on mathematical model (Fig. 3(a)) and process with a classical mathematical programming methods in order to have the optimal solution. Despite of multicriteria formulation for which making decision

[2]The systemic theory shows that each concrete system is governed by a set of parameters that are related to each other.
[3]For more information about nondominance order in the multicriteria optimization field, see (Ehrgott, 2005).

consists of the choice of an adequate solution from all efficient (best) solutions given by a multicriteria programming (Fig. 3(b)).



(a) Monocriteria approach: decision making on model



(b) Multicriteria approach: diversity of choice of solutions

Fig. 3. Modality of modelling: difference between monocriteria and multicriteria approach (Amine et al., 2009).

Techniques of transformation of a multicriteria model to a monocriteria formulation limit the choice of solutions. As against, multicriteria formulation makes possible making decision on the basis of local requirements. That is, the decision making is related especially to the node instead to all the network.
The choice of the adequate path is granted to the node (or the user) in order to respect local requirements which are difficult to be integrated into formal model and which change according to the circumstances. In the same connection, the diversity of solutions given, makes possible to have a backup path for each transmission in the network. Therefore, the approach may give more robustness and reliability to transmission behaviour, and in this context, an architecture, on the basis of a decision making system which controls the ad hoc network behaviour and guarantees the QoS, can be proposed.

5. Mathematical formulations

Several studies in ad hoc networking dealing especially with energy consumption, delay, fair scheduling, and so on, are considered as QoS oriented studies. This studies focus on a metric or a problematic from the ad hoc challenges, and aim at improving this issue.
In this respect, several studies have addressed the energy consumption, in ad hoc networks, that aim at improving techniques for energy conservation. These studies concern an important issue that affects the network behaviour. Indeed, the embedded energy in nodes of ad hoc networks are limited and hardly recharged or replaced, especially for military applications and sensor networks, therefore a meaningful strategy of energy control is desirable.
Energy constraint, from an algorithmic view, has been studied around two areas: minimal energy broadcasting problem and minimal energy multicasting problem. Broadcasting and multicasting represent a crucial issue in most of protocols in ad hoc networking field, because of their usefulness in discovering routes and transmission process.
Minimum Energy problem of Broadcast (MEB) and Multicast (MEM) is considered from a conceptual perspective as the problem of finding the arborescence with the minimum power

cost.

5.1 Minimum energy problems

5.1.1 Minimum energy problem of broadcast

Broadcasting is the process to send a message from a source to all active nodes in the network. It is characterized by no requirement of acknowledgement messages. The source is therefore called deaf source. This aspect of transmission, also known in some contexts as flooding, is an important issue in many network techniques as topology discovery and routing table construction.

Minimum Energy Broadcast problem, marked as MEB, consists to find a tree (arborescence) originated in the source s and relaying all active nodes; subject to minimizing the tree energy cost.

A probabilistic formulation of the MEB was presented in (Montemanni et al., 2008). It consists in associating each node i with a value $q_i \in]0,1[$ representing a probability that the node i still be active during the operability of the network. The approach is based on a level $\alpha \in]0,1[$ where a path is regarded as feasible if his probability, which is equal to the product of node probabilities, is greater or equal to α. The model developed is presented bellow:

$$\left\{\begin{array}{lll} \min \sum_{i\in V} y_i & & \\ \text{subject to} & & \\ y_i \geq p_{ij} z_{ij} & ; & \forall (i,j) \in A \\ \sum_{\substack{(i,j)\in A \\ i\in S, j\in V\setminus S}} z_{ij} \geq 1 & ; & \forall S \in V \quad , \quad s \in S \\ \sum_{(i,j)\in \mathcal{P}} z_{ij} \leq |P| - 1 & ; & \forall \mathcal{P} \in \mathcal{U} \\ z_{ij} \in \{0,1\} & ; & \forall (i,j) \in A \\ y_i \in I\!R^+ & ; & \forall i \in V \end{array}\right.$$

This model uses notations described in Tab. 1 above.

Symbol	Description
y_i	Transmission power of each node i
z_{ij}	Variable characterizing the optimal tree $\mathcal{T}$, i.e., $z_{ij} = \begin{cases} 1 & , \text{ if } (i,j) \in \mathcal{T} \\ 0 & , \text{ otherwise} \end{cases}$
$\lvert P\rvert$	Number of arcs belonging to path $\mathcal{P}$
$\mathcal{U}$	Set of all infeasible paths originated in s

Table 1. Minimum energy broadcast problem model description.

This model was the subject to develop two other models with more probabilistic aspect, namely cumulative probability formulation and multi-commodity flow formulation.

5.1.2 Minimum energy problem of multicast

Multicasting can be considered as a particular case of broadcasting; it consists to send a message from a source to more than one node in the network. The acknowledgment messages are required in this aspect though. Multicasting advantage consists in saving the embedded energy when the destination nodes are many, face to strategies that repeat transmission as many times as the number of destinations.

A QoS-MEM was formulated in (Guo & Yang, 2004) as a mixed integer linear programming model on the basis of the idea to extract a subgraph T_s^*, initiated in the source s and representing the bandwidth constrained multicast tree with minimum energy consumption, from the undirected graph $G(V, A)$. Let's consider the binary variable z characterizing T_s^* as

$$z_{ij} = \begin{cases} 1 & , \quad \text{if } (i,j) \in T_s^* \\ 0 & , \quad \text{otherwise} \end{cases} \tag{4}$$

and $t_{ij\kappa}$ is a binary variable which is equal to one if node i is scheduled to transmit to node j at slot κ, and zero otherwise. Let F_{ij} be a non-negative continuous variable representing fictitious flow produced by the multicast initiator s going through arc (i, j), and $q_{i\kappa}$ be a non-negative continuous variable representing the transmission power of the node i at slot κ.
Let's consider the following notation summarized in Tab. 2.
The model is so presented as follows

$$\begin{cases}
\min \sum\limits_{i \in N} \sum\limits_{i \in FS_i} q_{i\kappa} \\
\text{subject to} \\
\sum\limits_{\{j\,/\,(j,i)\in A\}} z_{js} = 0 \\
\sum\limits_{\{j\,/\,(j,i)\in A\}} z_{ji} = 1 & , \forall i \in M \setminus \{s\} \\
\sum\limits_{\{j\,/\,(j,i)\in A\}} z_{ji} \leq 1 & , \forall i \in N \setminus M \\
\sum\limits_{\{j\,/\,(j,i)\in A\}} z_{ij} \leq (n-1) \sum\limits_{\{j\,/\,(j,i)\in A\}} z_{ji} & , \forall i \in N \setminus M \\
\sum\limits_{\{j\,/\,(j,i)\in A\}} F_{ji} - \sum\limits_{\{j\,/\,(i,i)\in A\}} F_{ij} = \sum\limits_{\{j\,/\,(j,i)\in A\}} z_{ji} & , \forall i \in N \setminus \{s\} \\
z_{ji} \leq F_{ji} \leq (n-1)\, z_{ji} & , \forall i \in N \setminus \{s\}, (j,i) \in A \\
t_{ji\kappa} \leq z_{ji} & , \forall (j,i) \in A, \forall \kappa \in FS_j \\
\sum\limits_{\{j\,/\,(j,i)\in A\}} \sum\limits_{\{\kappa \in FS_j\}} t_{ji\kappa} = B \sum\limits_{(j,i)\in A} z_{ji} & , \forall u \in N \\
\sum\limits_{\{j\,/\,(j,i)\in A\}} t_{ij\kappa} \leq (n-1)\left(1 - \sum\limits_{\{j\,/\,(j,i)\in A\}} t_{ji\kappa}\right) & , \forall \kappa \in S, \forall i \in N \\
\frac{q_{ji}}{d_{ji}^{\alpha}} - \gamma \left(\eta + \sum\limits_{\substack{\{x\,/\,(x,i)\in A\} \\ x \neq j}} \frac{q_{x\kappa}}{d_{xi}^{\alpha}} \right) \geq \beta \left(t_{ji\kappa} - 1 \right) & , \forall \kappa \in S, \forall (j,i) \in A \\
q_{i\kappa} \leq p_i^{max} & , \forall i \in N \\
z_{ju}, t_{ji\kappa} \in \{0,1\} & , \forall (j,i) \in A, \quad \forall \kappa \in S
\end{cases}$$

This model contains two main categories of constraints: *rooted tree constraints* which characterize the multicast tree relaying the source s with all destinations. And *bandwidth constraints* defining the bandwidth QoS constraint in the MEM context; they reflect the conditions that bandwidth allocated on each link of the multicast tree should be conflict-free and meet the bandwidth requirement.
The Branch and Cut and Cutting Planes are proposed to provide efficient solution in static ad hoc networks with few nodes. This work, among other, was uncovered the challenge to cope with, in the energetic context, large scale networks, dynamic topology (in the mobility

Symbol	Description
n	Cardinality of V set.
M	The set of multicast nodes including the source node and all destination nodes.
α	Propagation loss exponent.
S	Set of time slots into which the bandwidth is partitioned.
TS_i	Set of transmission schedule of node i, defined as the power assignment in each time slot.
FS_i	A set of free time slots at node i defined as $FS_i = \{\kappa / P_{i\kappa} > 0, \kappa \in S\}$.
p_i^{max}	A maximum power value that a node i can use.
λ	The minimum signal to interference plus noise ratio.
η	The thermal noise at every receiver.

Table 2. Minimum energy multicast problem model description.

sense), and networks equipped with directional antenna.

This model presents a kind of QoS constrained MEB/MEM problem in static ad hoc networks or slowly-mobile ad hoc networks. In the same respect, several studies was addressed in the literature (Hashemi et al., 2007; Leggieri et al., 2008; Li et al., 2007; Montemanni & Gambardella, 2005; Yuan et al., 2008; etc) taking into account to find the covering tree with the exigency that all nodes still connected for broadcasting or multicasting purposes under the objective to minimize the energy consumption. In other words, it is the problem of assigning transmission power to the nodes in such a way that the total energy consumption over the network is minimized, subject to all the nodes still be connected. In this respect, a simplified formulation presented in (Leggieri et al., 2008) is stated as

$$\begin{cases} \min \sum_{i \in V} p_{ij} z_{ij} \\ \text{subject to} \\ \sum_{i \in S} \sum_{j \in K^i(S)} z_{ij} \quad \geq \quad 1 \quad , \quad \forall S \subset V, s \in S, D \cap S^c \neq \emptyset \\ \qquad\qquad x_{ij} \quad \in \{0,1\} \; , \qquad\qquad \forall (i,j) \in A \end{cases}$$

where the decision variable z_{ij}, characterizing the multicast tree as defined before, equal one if the energy available in node i can reach the node j, and zero otherwise.
Different solution methods were proposed in the literature for MEB/MEM problem with both exact and heuristic algorithms, discussing few difficulties of the proposed formulations as the number of some constraints and the efficiency of the returned solutions.
For more information about MEB/MEM problem, (Guo & Yang, 2007) provides a better understanding of the research challenges of energy-aware in ad hoc networks and gives an overview of methods and protocols developed according to this context.

5.2 Bicriteria model

In (Guerriero et al., 2009), authors have developed a model on the basis of the minimum path model introduced in (Skriver & Andersen, 2000), and accounts for the energy reserve and the link stability of mobile nodes.

$$\begin{cases} \min \sum\limits_{(i,j)\in A} m_{ij}(t)x_{ij} \\ \min \sum\limits_{(i,j)\in A} n_{ij}(t)x_{ij} \\ \text{subject to} \\ \qquad x_{ij}\,T_{ij}\,P_{ij}(t) \leq E_{res_i} \qquad , \qquad \forall (i,j)\in A \\ \qquad x_{ij}\,T_{ij}\,Q_{ij}(t) \leq \delta E_{res_j} \qquad , \qquad \forall (i,j)\in A \\ \sum\limits_{\{j\,/\,(i,j)\in A\}} x_{ij} - \sum\limits_{\{j\,/\,(i,j)\in A\}} x_{ji} = \begin{cases} 1 & \text{if} \quad i=s \\ 0 & \text{if} \quad i\in\mathcal{N}\setminus\{s,d\} \\ -1 & \text{if} \quad i=d \end{cases} \\ \qquad x_{ij} \in \{0,1\} \qquad , \qquad \forall (i,j)\in A \end{cases}$$

where

$$\begin{aligned} m_{ij}(t) &= \frac{P_{ij}(t)}{PR_j(t)} \quad , \quad \forall (i,j)\in A \\ d_{ij}^{avg} &= \frac{\sum\limits_{k=1}^{|\mathcal{O}_{ij}|} d_{ij}^{(k)}}{|\mathcal{O}_{ij}|} \quad , \quad \forall (i,j)\in A \\ n_{ij}(t) &= \frac{d_{ij}^{avg}}{P_{ij}(a_{ij})k} \quad , \quad a_{ij}\in\{0,\dots,A_{max}\} \quad , \quad \forall (i,j)\in A \end{aligned}$$

The key notation that has been used in this model is described in Tab. 3.

Symbol	Description
m_{ij}	Energy coefficient of link (i,j)
n_{ij}	Stability of link (i,j) coefficient
$d_{ij}^{(k)}$	Observation of link (i,j) at time k
T_{ij}	Time required to send a packet of information from node i to node j
P_{ij}	Power dissipated in transmission over link (i,j)
Q_{ij}	Power wasted in the reception
δ	A parameter from $]0,1[$
E_{res_i}	Residual energy in node i
PR_i	Propensity of node i
R_{ij}	Residual life time of link (i,j)
d_{ij}^{avg}	Average traveled distance between nodes i and j
$\mathcal{O}_{ij}$	Flow on link (i,j)

Table 3. Bi-criteria model description.

Authors have transformed this model to a monocriteria model by combining the two objectives into a weighted convex sum

$$\min \sum_{(i,j)\in A} \Big(p_1\, m_{ij}(t) + p_2\, n_{ij}(t)\Big)\, x_{ij}$$

Like any classical scalarisation method, the variation of the parameters p_1 and p_2 (subject to $p_1 + p_2 = 1$) provides few solutions where each one refers to a preference structure. Authors

used the greedy hop by hop approach with the aim to balance the opposite effects of an energy aware routing that tries to select longer routes and a routing algorithm that desires to find a more stable path through the selection of a shorter route. Simulations show the balanced weight p_1 and p_2 which can offer a better network behaviour and which allows to give the optimal trade-off between low energy consumption and high stability link level.
The main observation on this approach lies in few QoS criteria ignored in the model as well as QoS constraints that characterize the ad hoc network nature. All these parameters should be taken into account in order to guarantee best quality of service.

5.3 Multicriteria model based on four criteria

The model developed in (Amine et al., 2009) consists of a model with four criteria; namely, energy consumption, delay, bandwidth, and packets loss rate:

$$\begin{cases} \min \sum_{(i,j)\in A} x_{ij} p_{ij} \\ \max_{\mathcal{P}} \min_{(i,j)\in A} x_{ij} B_{ij} \\ \min \sum_{(i,j)\in A} x_{ij} D_{ij} \\ \min \tau_{\mathcal{P}} \\ \text{subject to} \\ \quad p_{ij} = p_{ji} \quad , \quad \forall (i,j) \in A \\ \quad B_P \geq B_{\min} \\ \quad D_P \leq D_S \\ \quad p_{ij} = t_{ij} + \varepsilon_{ij} \quad , \quad \forall (i,j) \in \mathcal{P} \\ \quad D_{ij} B_{ij} \geq f_{ij} \quad , \quad \forall (i,j) \in \mathcal{P} \\ \quad \tau_{\mathcal{P}} < \pi \\ \quad x_{ij} \in \{0,1\} \quad , \quad \forall (i,j) \in A \end{cases}$$

The key notation that has been used in this model is described in Tab. 4 below.

Symbol	Description
$\mathcal{P}$	Routing path
x_{ij}	Decision variable
p_{ij}	Energy affected to the link (i,j)
B_{ij}	Bandwidth available on link (i,j)
D_{ij}	End to end delay on link (i,j)
D_S	A maximal value that D_{ij} must not exceed
τ_P	Packets loss rate
π	A maximal value that $\tau_{\mathcal{P}}$ must not exceed
t_{ij}	Energy required to reach a node j from a node i
ε_{ij}	Insurance factor depending of link (i,j)
f_{ij}	Flow on link (i,j)

Table 4. Four-criteria model description.

This model takes into account a number of criteria that are not treated before. However, the consideration of the bandwidth and the delay in a contradiction hypothesis in not generally correct. Indeed, in a perfect network, the delay and the bandwidth are related by the formula

$$D_{ij} B_{ij} = f_{ij} \tag{5}$$

where D_{ij} and B_{ij} are, respectively, the delay and the bandwidth available on a link (i, j), and f_{ij} is the flow to be transmitted over (i, j). Thus, this model may be compatible only with networks with more disturbance according to extra delay affected, eventually, by space conditions and bit errors occurring in nodes (Amine et al., 2009; Korhonen & Wang, 2005). Simulations show that this approach, until it returns numerous paths according to different QoS preferences, gives effectively more choice to the user in the routing process.

6. Conclusion

The quality of service presents a rich field for study in ad hoc networking. It concerns the behaviour of the network, and is dealt with from different points of view. In the current studies, QoS models, QoS resource reservation, QoS routing, and medium access control protocol are stated specifically. From a mathematical point of view, QoS presents an economic problem which consists to optimize an objective cost under several constraints imposed by the network nature and proprieties. In this connection, several models are developed in the literature for or oriented to quality of service.

Mathematical models of quality of service give virtual maquettes representing some aspects aiming at improving the quality of service with mathematical techniques. Mathematical models of quality of service in ad hoc networking involve two different formalities: monocriteria formulations that focus on one aspect of QoS (energy, bandwidth, delay, etc), and multicriteria formulations that take into account a set of no less than two contradictory aspects of QoS and give more realistic representation.

Monocriteria formulations were largely addressed in the literature and gave efficient approach for many concerns of quality of service in ad hoc networking. Furthermore, several results have been already integrated in many standard protocols. In the same respect, various challenging issues were raised which provide currently a large scope for investigation.

Multicriteria formulations present a realistic feature to study the quality of service in ad hoc networking since the QoS criteria are affected by each other and cannot be optimized separately. These formulations are usually dealt with by adopting few techniques in order to transform the formulation into a monocriteria one for which classical methods and algorithms can be used. Solving each transformed formulation gives an efficient solution according to a preference structure. As against, few studies aim at finding the Pareto Front of the original multicriteria formulation in order to give all preference structures which are related to all users' satisfaction. This point of view gives more opportunities in decision making. For this, more attention should be given to the diversity of choice in multicriteria approaches in order to satisfy all quality of service levels related to all classes of users. A crucial feature to fulfill this intention is firstly to develop rigorous mathematical formula characterizing the relationship between parameters in ad hoc networking field as delay, bandwidth, packet loss rate, and so on. Secondly, to improve the conception and the modelling process in the sense that the diversity of choice aims at proposing a totalitarian approach which guarantees the quality of service in an extended meaningful way.

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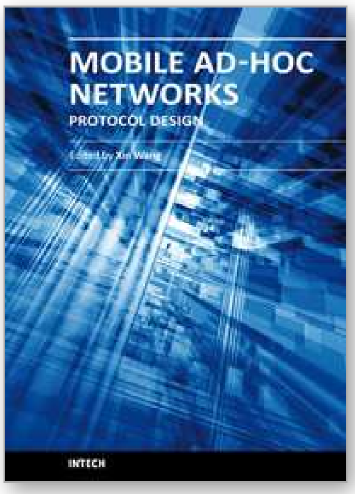

Mobile Ad-Hoc Networks: Protocol Design
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Being infrastructure-less and without central administration control, wireless ad-hoc networking is playing a more and more important role in extending the coverage of traditional wireless infrastructure (cellular networks, wireless LAN, etc). This book includes state-of-the-art techniques and solutions for wireless ad-hoc networks. It focuses on the following topics in ad-hoc networks: quality-of-service and video communication, routing protocol and cross-layer design. A few interesting problems about security and delay-tolerant networks are also discussed. This book is targeted to provide network engineers and researchers with design guidelines for large scale wireless ad hoc networks.

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