Ad Hoc Wireless Networks

Ad Hoc Wireless Networks: A Communication-Theoretic Perspective Ozan K. Tonguz and Gianluigi Ferrari
ISBN: 0-470-09110-X

Ad Hoc Wireless Networks

A Communication-Theoretic Perspective

Ozan K. Tonguz
Carnegie Mellon University, USA

Gianluigi Ferrari
University of Parma, Italy

John Wiley & Sons, Ltd

Copyright © 2006 John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester,
West Sussex PO19 8SQ, England

Telephone (+44) 1243 779777

Email (for orders and customer service enquiries): cs-books@wiley.co.uk
Visit our Home Page on www.wiley.com

All Rights Reserved. No part of this publication may be reproduced, stored in a retrieval system or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning or otherwise, except under the terms of the Copyright, Designs and Patents Act 1988 or under the terms of a licence issued by the Copyright Licensing Agency Ltd, 90 Tottenham Court Road, London W1T 4LP, UK, without the permission in writing of the Publisher. Requests to the Publisher should be addressed to the Permissions Department, John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex PO19 8SQ, England, or emailed to permreq@wiley.co.uk, or faxed to (+44) 1243 770620.

Designations used by companies to distinguish their products are often claimed as trademarks. All brand names and product names used in this book are trade names, service marks, trademarks or registered trademarks of their respective owners. The Publisher is not associated with any product or vendor mentioned in this book.

This publication is designed to provide accurate and authoritative information in regard to the subject matter covered. It is sold on the understanding that the Publisher is not engaged in rendering professional services. If professional advice or other expert assistance is required, the services of a competent professional should be sought.

Other Wiley Editorial Offices

John Wiley & Sons Inc., 111 River Street, Hoboken, NJ 07030, USA

Jossey-Bass, 989 Market Street, San Francisco, CA 94103-1741, USA

Wiley-VCH Verlag GmbH, Boschstr. 12, D-69469 Weinheim, Germany

John Wiley & Sons Australia Ltd, 42 McDougall Street, Milton, Queensland 4064, Australia

John Wiley & Sons (Asia) Pte Ltd, 2 Clementi Loop #02-01, Jin Xing Distripark, Singapore 129809

John Wiley & Sons Canada Ltd, 22 Worcester Road, Etobicoke, Ontario, Canada M9W 1L1

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books.

British Library Cataloguing in Publication Data

A catalogue record for this book is available from the British Library

ISBN-13 978-0-470-09110-4 (HB)
ISBN-10 0-470-09110-X (HB)

Typeset by Sunrise Setting Ltd, Torquay, Devon, UK.
Printed and bound in Great Britain by Antony Rowe Ltd, Chippenham, Wiltshire.
This book is printed on acid-free paper responsibly manufactured from sustainable forestry in which at least two trees are planted for each one used for paper production.

To Inci, Dilek, Cihan and Tonguz
Ozan K. Tonguz

To Anna
Gianluigi Ferrari

Contents

Preface

The book is not a treatise on all aspects of wireless ad hoc networks and sensor networks. Rather, it attempts to bridge the gap between different viewpoints on the subject (the most prominent ones being the routing-based approach, the information-theoretic approach, the dynamic control approach, and the game-theoretic approach amongst others). To be very clear about this, we re-emphasize that all of these approaches are important approaches in their own right. In other words, they magnify a certain aspect of the 'big picture' and study it in detail. In this sense, they emphasize the *part* as opposed to the *whole*. In this book, we attempt to do the latter.

We propose a 'bottom-up' approach for understanding the interdependencies and interrelationships of different layers of the protocol stack in terms of designing wireless ad hoc (and sensor) networks. To that end, we present a communication-theoretic viewpoint of how to understand 'the whole', whereby the capabilities and limitations of the physical layer are shown to heavily affect, if not determine, the choices and performance that one can hope to obtain at higher layers. This is a judicious choice on the authors' part and it is in contrast to the conventional top-down approach typically used in computer networking. We feel that wireless ad hoc networks (and sensor networks), depending on the application at hand, can dictate challenging physical layer conditions in terms of wireless channels (fading, shadowing, scattering, etc.), power requirements, interference, etc. and this is in stark contrast to the reliable channel and physical layer conditions encountered in today's fiber-optics based computer networks. This is the main rationale behind our 'bottom-up' approach.

It should be noted that the specific protocols used in this book (such as RESGO and RESLIGO at the MAC layer and reservation-based versus non-reservation-based switching/routing at the network layer) serve as representative protocols as opposed to the optimum or recommended protocols. As such, one could argue that some of the protocols and mathematical models used in our book correspond to ideal cases as opposed to practical cases. While this might be true for some of our protocols and models, these somewhat idealized mathematical models serve a very important purpose; namely, showing the interrelationship of the physical layer in wireless ad hoc networks with higher layers. It is our belief and hope that the important insights gained in this book will pave the way for studying other (and perhaps more practical) protocols and models as well.

Notwithstanding the unified approach presented, transport layer and application layer details are not dealt with in this edition of our book. We are currently investigating these issues as well. These are important emerging research areas and it remains to be seen what the best approach would be for dealing with the details of these layers in the protocol stack.

As an extra resource we have set up a companion website for our book containing a sample chapter. Also, for those wishing to use this material for lecturing purposes, electronic versions of most of the figures from our book are available. Please go to the following URL and take a look: http://www.wiley.com/go/tonguz

It is a pleasure to express our indebtedness to our colleagues and students who were there when the material in this book took shape during the last four years. One can hardly imagine a more stimulating research environment than Carnegie Mellon University (CMU). In particular, the PhD students of the first author (O.K. Tonguz), Mr Sooksan Panichpapiboon and Miss Nawaporn Wisitpongphan of CMU, made major contributions to Chapters 7–9 of the book. We are very grateful to both of them and other colleagues at CMU. The authors would also like to acknowledge the funding received from Cylab of CMU that partially sponsored this ambitious project. Last but not least, we extend our sincere gratitude to Mark Hammond and Sarah Hinton of John Wiley & Sons, Ltd for facilitating this interesting project, for their kindness all along and for their patience.

O. K. Tonguz & G. Ferrari
Pittsburgh
USA

List of Acronyms

ACK	ACKnowledgement
A-D	Analog–digital
AP	Access point
ARQ	Automatic repeat request
AWGN	Additive white Gaussian noise
BER	Bit error rate
BPSK	Binary phase shift keying
BS	Base station
CDF	Cumulative distribution function
CDMA	Code division multiple access
CSMA	Carrier sense multiple access
CSMA/CA	CSMA with collision avoidance
CSMA/CD	CSMA with collision detection
CTS	Clear to send
CUR	Channel utilization ratio
DAB	Digital audio broadcasting
DES	Delay estimation scheme
DNP	Direction-non-persistent
DP	Direction-persistent
DSR	Dynamic source routing
DSRC	Dedicated short-range communications
DVB	Digital video broadcasting
ECUI	Effective channel utilization interval
FAS	Flow adaptation scheme
FDMA	Frequency division multiple access
FEC	Forward error correction
4G	Fourth generation
iCAR	Integrated cellular and ad hoc relay
IF	Intermediate frequency
INI	Inter-node interference
IP	Internet protocol
ISM	Industrial, scientific and medical
LAN	Local area network
LRS	Limited receiver sensitivity
MAC	Medium access control

MACA	Multiple access collision avoidance
MAN	Metropolitan area network
MIMO	Multiple input multiple output
NLP	Non-local percolation
NP	Non-polynomial
NRB	Non-reservation-based
NRNSCC	Non-recursive non-systematic convolutional code
OFDM	Orthogonal frequency division multiplexing
ONRBS	Opportunistic non-reservation-based switching
PER	Packet error rate
PHY	PHYsical
P2P	Peer-to-peer
QoS	Quality of service
RB	Reservation-based
RBS	Reservation-based switching
RCUI	Reserved channel utilization interval
RESCHOGO	Reserve-choose-and-go
RESGO	Reserve-and-go
RESLIGO	Reserve-listen-and-go
RTQ	Route quality
RTS	Request to send
RSCC	Recursive systematic convolutional code
SCCC	Serially concatenated convolutional code
SIR	Signal-to-interference ratio
SNR	Signal-to-noise ratio
SP	Shortest path
SS	Subsidiary station
S-RESGO	Spread-reserve-and-go
TCP	Transport control protocol
TDMA	Time division multiple access
UMTS	Universal mobile telecommunication system
ZRP	Zone routing protocol
Wi-Fi	Wireless fidelity
WiMAX	Worldwide interoperability for microwave access
WLAN	Wireless local area network
WMAN	Wireless metropolitan area network

Chapter 1

Related Work and Preliminary Considerations

1.1 Introduction

In this chapter we take a preliminary look at *ad hoc wireless networks*. This is currently a hot research area, especially because there is an increasing need for connectivity 'anywhere' and, in particular, 'anyhow' (with and without a fixed infrastructure). While traditional networks have fixed nodes with wired connections (either optical fibers or copper lines), ad hoc wireless networks can, in general, be described as *multi-hop wireless networks* with *mobile* nodes. However, the mobility condition can be relaxed, and we can identify an ad hoc wireless network as a network where all the nodes are connected through wireless links, and where there is not a central or dominant node – as opposed to, for example, the case of cellular wireless networks where a base station (BS) exists in each cell. All the nodes in an ad hoc wireless network are at the same hierarchical level. In this sense, sensor networks can be regarded as a special case of ad hoc wireless networks.

Communication design in an ad hoc wireless network in a very general and meaningful way is a very challenging and complicated task [1]. The simple fact that the communication design should be sufficiently general to incorporate both the case of fixed nodes and mobile nodes is, in and by itself, a difficult objective to meet. This chapter is a preliminary high-level assessment of the situation, with the aim of understanding 'how' an ad hoc wireless network should be designed. In particular, we are concerned with the capabilities and limitations that the *physical layer* imposes on the network performance. In fact, most of the existing literature focuses on higher layers (such as the network and medium access control (MAC) layers), 'taking for granted' that the lower layers, and in particular the physical layer, can successfully cope with the channel impairments. This assumption is reasonable in networks with very reliable communication links (e.g. fixed optical networks). However, this assumption is much less meaningful in the case of wireless networks, where the radio communication links are very unreliable and subject to weather and environmental conditions. This leads to a more severe channel distortion (e.g. channels with fading, either non-selective or selective). Hence, it is necessary to take into account the channel characteristics in designing an ad hoc wireless network. In particular, it is desirable to come up with an integrated design comprising both the physical, MAC and network layers. This is the goal of the remaining chapters of this book.

Ad Hoc Wireless Networks: A Communication-Theoretic Perspective Ozan K. Tonguz and Gianluigi Ferrari
ISBN: 0-470-09110-X

The remainder of this chapter is organized as follows. In section 1.2, we briefly review the various approaches for the design and analysis of an ad hoc wireless network that appeared in the literature. In section 1.3, we make simple and preliminary considerations for a more meaningful approach to the design of an ad hoc wireless network, taking into account the physical layer. In section 1.4, an overview of the major underlying assumptions considered in this book is presented. Section 1.5 concludes the chapter and provides the reader with an overview of the main philosophy behind the book.

1.2 Related Work

Ad hoc wireless networks have attracted a lot of attention over the last few years, because of the increasing demand for ubiquitous connectivity. As mentioned in section 1.1, the design of ad hoc wireless networks seems to require novel approaches, since they have peculiar characteristics which differ substantially from those of fixed networks or cellular networks, for which well-established design techniques already exist [2]. In the following, we briefly describe the main approaches that have appeared in the literature, indicating the potential limitations that are apparent at a first glance. However, it is fair to say that these limitations are understandable, since there are several constraints and it seems very difficult to take all of them into account simultaneously. Our final goal is to obtain a very general and adaptive model, and the simple considerations in section 1.3 point in this direction. We want to underline that the references considered in the following are by no means complete, and represent just a few samples of the much vaster ensemble that have appeared in the literature.

1.2.1 A Routing-Based Approach

Considering an ad hoc wireless network, a simple and immediate way to visualize it is to consider a set of *nodes* or *dots* distributed over a surface. These dots may be moving. Each node may want to communicate with another node in the network, hence the communication system needs to ensure that a *packet* sent by the starting node, the *source*, will eventually reach the intended node, i.e. the *destination*.

In a fixed network, one strives to find the shortest sequence of segments or *links* – each segment having two nodes at its end points – connecting the source with the destination. In this case, the focus is mainly on *routing*. However, in order for each node of this *route* to know which is the next node to forward a received packet to, it is required that each node has perfect knowledge of the network topology. This vision is very simplistic, and assumes that the transmission on each link corresponds to an error-free transfer of information. If this were the case, then it would be reasonable to only focus on routing. This, unfortunately, is not the case with links constituted by radio channels, hence this approach could be very limited for ad hoc wireless networks.

If the nodes are moving, then it is tempting to simply extend the above approach, focusing on the design of routing strategies which try to track the evolution of the network's topology. For example, extensions of the transport control protocol (TCP) to a mobile environment were proposed [3]. This is also the approach considered in almost all the possible routing protocols presented in [4]. In particular, the solutions proposed in [4] range from *proactive* routing protocols, where an updated description of the network topology is maintained at each node, to *reactive* routing protocols, which dynamically try to adapt to the changing conditions only if needed. In some cases, the authors claim that the numerical results account for realistic radio channel models, but it often seems that the physical layer is simply ignored. In all of these cases, it is assumed that the physical layer makes each link in the network an error-free connection. Hence, each node should only worry about the forwarding of an incoming packet. In this way, the focus again shifts to routing.

It is important to observe that some of the proposed protocols are interesting, and the underlying ideas are meaningful. For example, the dynamic source routing (DSR) protocol [5] and the zone routing protocol (ZRP) [6] are totally *on-demand* protocols, and the underlying ideas seem extendible to a more general design of wireless networks based on realistic physical constraints. The concept of associativity-based routing (ABR) [7–9] is also interesting: it indicates that the route to be preferred should not be the shortest one, but the one passing through the densest area of the network. This should ensure the longest possible route lifetime. The concept of *flooding* [10] and on-line local estimation based on a very few observables [11] also seem significant. Geographic random forwarding is considered in [12, 13]. A nice overview of architectures and protocols for ad hoc wireless networks is presented in [14].

1.2.2 An Information-Theoretic Approach

One of the fundamental and most intriguing concepts in information theory is the concept of the *capacity* of a single communication channel, measured in bits per second [15]. In a network, an extension of this concept leads to the *transport capacity* of a network, given by the product between the data-rate (b/s) and the distance (m) through which the bits can be carried. The transport capacity can also be interpreted as a measure of the *goodput* of the network [2]. This is intuitive, since the throughput increases either if the network can transport a few bits for a long range or many bits for a short range. In order to evaluate this theoretical network communication limit, information theorists allow themselves to make some unrealistic assumptions, for example in terms of routing strategy or MAC protocols. In [16], a first approach to the computation of the transport capacity of a network with fixed nodes is considered. The main result is that in a wireless network with N nodes distributed in a finite circle or sphere, with optimal *placement* of the nodes, optimally chosen *traffic pattern* and optimally chosen *transmission range*, the transport capacity is $\Theta(\sqrt{N})$, where the notation $\Theta(\cdot)$ indicates that the transport capacity is asymptotically, i.e. for $N \to \infty$, of the order of $\sqrt{N}$ [17]. This implies that the throughput per node is $\Theta(1/\sqrt{N})$. Hence, in a network with increasing node density – observe that the area where the N nodes fit is finite – the throughput per node goes to zero. This is somewhat obvious, since the number of hops that a generic packet has to make increases without limit. It is clear that this result, besides the optimality conditions mentioned above, does not consider at all the *delay* characterizing a packet transmission. While in [16] the authors claim that mobility should further reduce the transport capacity of a wireless network, in [18] this conclusion is challenged and the opposite is proved true. In [18], however, the authors make some unrealistic assumptions which justify their results. They assume that the buffering capacity of each node is unlimited and that a node perfectly recognizes when it can communicate to the nearest neighbor with a signal-to-interference ratio (SIR) above a given threshold. Moreover, there is no delay constraint. Given these premises, the routing idea is simply implemented by the following two phases. When a source node $\mathrm{n_S}$ wants to transmit a packet, it waits for the first node $\mathrm{n_R}$ passing by and transmits the packet to it. If this node is not the destination, then it becomes a *relay* node. This means that node $\mathrm{n_R}$ stores the received packet and keeps on wandering in the limited area. Whenever it comes near to the desired destination node $\mathrm{n_D}$, it just delivers the packet. As one can see, this is a very efficient communication protocol (they refer to it as *multiuser* *diversity routing*), with the least possible number of hops. However, it is obvious that this is a highly unrealistic communication protocol and could lead to very large delays (presumably not infinite, since the area where the nodes move is finite).

The information-theoretic approaches that recently appeared in the literature consider *ad hoc* conditions in order to maximize the transmission of information in the network. Constraints such as delay, storing capacity, realistic moving patterns (where a node is free to go away), power consumption and the impossibility of knowing the current SIR are simply not considered. While the concept of the capacity of a single-input single-output channel introduced by Shannon is a definite, simple and meaningful concept which represents a useful limit to take into account, it seems that an equivalent meaningful quantity for an ad hoc wireless network has not been clearly identified yet – the concept of *transport capacity*, however, well describes the information transfer in the network. The concept of *capacity per unit cost* [19] might be a possible candidate as well. An interesting information-theoretic perspective on multiaccess channel is presented in [20].

1.2.3 A Dynamic Control Approach

Wireless networks can be modeled as dynamic systems, where many parameters, for example the transmission protocols of each node, need to be dynamically adjusted [21]. In this sense, control theory could provide useful tools for the analysis of the network behavior. An approach of this type is suggested in [22], where the authors propose a routing scheme converging with probability one to the set of approximate *Cesaro–Wardrop equilibria*, which are suitably defined. The proposed adaptive scheme has two components: an iterative delay estimation scheme (DES) and an iterative flow adaptation scheme (FAS). The basic idea is that of associating to each node a particular time-varying flow, and then adjusting the flows from each node based on a few observables. It is possible to derive a set of ordinary differential equations in the flows, whose solution returns the steady-state behavior of the network. From this idea, in [23] a load adaptive routing protocol is proposed. It is arguable that a dynamic control approach could be meaningful in analyzing the convergence of the network flows structure. However, it seems difficult to use this tool to effectively define a communication protocol. It is easy to see that in this case also, a possible network analysis concentrates mainly on routing based on network flows.

1.2.4 A Game-Theoretic Approach

To date, it seems that there is no complete game-theoretic approach for the design of ad hoc wireless networks or, more generally, communication networks. The game which somehow seems to be more related with a communication network is the *maximum flow game*. Given a directed graph and identifying a source and a destination, the maximum flow associated with a particular subset of nodes is given by all the source–destination arc-distinct paths which can be obtained with the considered set of nodes. This game belongs to the class of combinatorial optimization games [24], as shown in [25]. The solutions of a game are generally related to the concept of the *core* of a game, which is a well-defined set of real vectors associated with the game structure. In [26] the authors show that proving that a real vector is not a core member of the maximum flow game is NP-complete. This, in turn, is equivalent to saying that finding the ensemble of flows in all the links which attain the maximum total flow is NP-complete.

It is still not very clear how the concept of a maximum flow game could be used in designing a communication protocol for an ad hoc wireless network. However, it is important to observe that most of the techniques used in combinatorial optimization games reduce to integer linear programming techniques. In this sense, linear and nonlinear programming techniques [27] could be very important tools in fixing the network parameters. In fact, given a meaningful objective function with variables representative of the ad hoc wireless network, and given a set of meaningful constraints, optimization theory leads to the solution of this problem in many cases.

1.3 A New Perspective for the Design of Ad Hoc Wireless Networks

In section 1.2, a quick overview of the main approaches recently reported for the design and analysis of an ad hoc wireless network was given. One can see that none of these approaches explicitly considers the *physical layer*, which plays a fundamental role in the case of radio channels. While in fixed networks it is reasonable to leave to higher levels the task of reconstructing the transmitted stream of information, for example requesting retransmission of a damaged packet (e.g. using automatic repeat request, ARQ), in ad hoc wireless networks the physical layer probably plays a fundamental role in combating the channel impairments. Moreover, most of the approaches considered in section 1.2 do not take into account (deliberately or inadvertently) some 'real' constraints in ad hoc wireless networks, such as:

- battery power consumption: this is a major limitation, since once a node has exhausted its power, it cannot support any communication. Hence, its power consumption affects the entire community, not only the node itself;
- network area: most of the results in the literature assume that all the nodes are confined to a precise surface with finite area. It is obvious that if the nodes move too far part, then radio communication is impossible. However, the communication protocol should accommodate a very general topological situation, where some nodes may go away;
- throughput and delay: the evaluation of these parameters, and in particular of their ratio, is fundamental. None of the results in section 1.2 clearly considers this performance parameter.

We now consider a simple approach, trying to figure out what happens when a source node, $\mathrm{n_S}$, comes into an area where there *may* be other nodes, and needs to link itself to the network. We assume that there is global addressing, i.e. each node is associated with a unique address (for example, this will be the case in version 6 of the internet protocol, IPv6), and each node knows the desired destination address. We assume that each node is equipped with an omnidirectional antenna. We also assume that it is possible to quantify the *spatial density* of the nodes, and we define this parameter as ρ_S. A node may not be given this parameter. As soon as a node needs to communicate, it starts looking around to see if there are nodes in its proximity. For example, it could send a 'hello' message, or even the first packet of the information it needs to transmit – this implicitly assumes packetized data transmission. Given the omnidirectionality of the antennas, one can visualize the propagation of a message as an expanding *bubble* and we will refer to the transmission of a packet from a node as *bubbling*.

When the transmit power is depleted by the channel and the information is by and large unrecoverable, we assume that the bubble 'blows up'. If another node is reached by the bubble before it blows up, then this node can return an acknowledgment (ACK), i.e. bubbles back, to notify its presence. This analogy of bubbling can be formalized in the context of the theory of *continuum percolation* [28–30], which represents a statistical tool to analyze and characterize planar random processes. In [31], the authors consider *broadcast percolation* and in [32] this theory is applied to evaluate the impact of the use of BSs in sparse ad hoc wireless networks, to improve the likelihood of percolation. Note that this theory pertains to other scientific areas, besides engineering (e.g. molecular biology, disease spread study, etc.). In the case of ad hoc wireless networks, and in particular in the communication-theoretic approach proposed in the next chapters, this theory could play a major role in the *route discovery* (or *joining*) phase. After node $\mathrm{n_S}$ has sent its request to set up a route, if no node replies to the sent message, node $\mathrm{n_S}$ can proceed in other ways.

- The original transmit power per node, P_t, might be insufficient. If the node knew ρ_S, it could assume $P_\mathrm{t} \propto 1/\rho_\mathrm{S}$, i.e. the larger the number of nodes in the region, the lower the power that a node needs to reach its nearest neighbor. In any case, $\mathrm{n_S}$ bubbles with $P'_\mathrm{t} > P_\mathrm{t}$ and sees what happens.

- Given that the node can move, after reaching a predefined transmission power threshold P_t^th, the node can decide to move, following a pattern which brings it over a circle centered on its original position. It then moves repeatedly over the circle, bubbling from each new position. It can then transfer to an external circle and repeat the search. After a prespecified number of moves it stops.

The joining phase indicated above (repeated bubbling and moving) is limited by the finite amount of energy available at a node. If a node cannot keep contact with any other node, then it just stops and waits for some other node to pass by.

After the joining phase, we assume that $\mathrm{n_S}$ has at least a neighboring node. We assume that each node may keep track of its nearest neighbors only, defined as those reachable with a bubble – a node cannot have knowledge of the entire network topology, in order to account for any mobility pattern. Let us assume that $\mathrm{n_S}$ wants to communicate with another node $\mathrm{n_D}$, which is not one of its neighbors. A *percolation* process should start. One can visualize this as a sort of progressive bubbling, as shown in Figure 1.1: the nodes hit by the bubble generated by $\mathrm{n_S}$ generate new bubbles, and the external nodes hit by these bubbles in turn repeat the process, and so on. Hopefully, at some point $\mathrm{n_D}$ is hit by one of these bubbles. At this point, $\mathrm{n_D}$ starts sending back an acknowledgment, which should hopefully propagate back to $\mathrm{n_S}$ (along the discovered route), creating what could be defined as a *communication tube*, rather than a specific route. In Figure 1.2, a possible communication tube is shown. As one can see, it is not a fixed route, but nodes are allowed to exit and enter the communication tube, which can 'bend' in order to preserve connectivity.

Before describing the route maintenance phase, we briefly comment on the *multi-hop* nature of the packet transmission in an ad hoc wireless network. In the classical view of a fixed network [2], the communication links are assumed to be almost error-free. Hence, when a node receives a packet and forwards it to the next node, it is implicitly assumed that the integrity of the packet is preserved. However, this is far from obvious in an ad hoc wireless network, where usually each radio communication link rapidly degrades the quality of the transmitted modulated symbols. *Regeneration* at each node becomes fundamental. In order to perform regeneration, a forward error correction (FEC) strategy is very attractive.