Full text available at: http://dx.doi.org/10.1561/1300000047

Modern Random Access Protocols

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the essence of knowledge
Boston — Delft

Full text available at: http://dx.doi.org/10.1561/1300000047

Foundations and Trends® in Networking

Published, sold and distributed by:
now Publishers Inc.
PO Box 1024
Hanover, MA 02339
United States
Tel. +1-781-985-4510
www.nowpublishers.com
sales@nowpublishers.com

Outside North America:
now Publishers Inc.
PO Box 179
2600 AD Delft
The Netherlands
Tel. +31-6-51115274

The preferred citation for this publication is

M. Berioli, G. Cocco, G. Liva and A. Munari. *Modern Random Access Protocols.* Foundations and Trends® in Networking, vol. 10, no. 4, pp. 317–446, 2015.

This Foundations and Trends® issue was typeset in LaTeX using a class file designed by Neal Parikh. Printed on acid-free paper.

ISBN: 978-1-68083-216-7
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Foundations and Trends® in Networking, 2015, Volume 10, 4 issues. ISSN paper version 1554-057X. ISSN online version 1554-0588. Also available as a combined paper and online subscription.

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Foundations and Trends® in Networking
Vol. 10, No. 4 (2015) 317–446
© 2016 M. Berioli, G. Cocco, G. Liva and A. Munari
DOI: 10.1561/1300000047

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Full text available at: http://dx.doi.org/10.1561/1300000047

Abstract

Random access represents possibly the simplest and yet one of the best known approaches for sharing a channel among several users. Since their introduction in the 1970s, random access schemes have been thoroughly studied and small variations of the pioneering Aloha protocol have since then become a key component of many communications standards, ranging from satellite networks to ad hoc and cellular scenarios. A fundamental step forward for this *old* paradigm has been witnessed in the past few years, with the development of new solutions, mainly based on the principles of successive interference cancellation, which made it possible to embrace constructively collisions among packets rather enduring them as a waste of resources. These new lines of research have rendered the performance of *modern* random access protocols competitive to that of their coordinated counterparts, paving the road for a multitude of new applications.

This monograph explores the main ideas and design principles that are behind some of such novel schemes, and aims at offering to the reader an introduction to the analytical tools that can be used to model their performance. After reviewing some relevant results for the random access channel, the volume focuses on slotted solutions that combine the approach of diversity Aloha with successive interference cancellation, and discusses their optimisation based on an analogy with the theory of codes on graphs. The potential of modern random access is then further explored considering two families of schemes: the former based on physical layer network coding to resolve collisions among users, and the latter leaning on the concept of receiver diversity. Finally, the opportunities and the challenges encountered by random access solutions recently devised to operate in asynchronous, i.e., unslotted, scenarios are reviewed and discussed.

M. Berioli, G. Cocco, G. Liva and A. Munari. *Modern Random Access Protocols*.
Foundations and Trends® in Networking, vol. 10, no. 4, pp. 317–446, 2015.
DOI: 10.1561/1300000047.

Full text available at: http://dx.doi.org/10.1561/1300000047

Acronyms

ARQ automatic repeat request

AWGN additive white Gaussian noise

bpcu bits per channel use

CC code combining

CDMA code division multiple access

CER codeword error rate

CRA contention resolution Aloha

CRDSA contention resolution diversity slotted Aloha

CoMP coordinated multi-point

CSA coded slotted Aloha

CSI channel state information

DNF denoise-and-forward

EM expectation maximisation

E-SSA enhanced spread spectrum Aloha

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eNB eNodeB

FDMA frequency division multiple access

FEC forward error correction

i.i.d. independent and identically-distributed

IRSA irregular repetition slotted Aloha

LDPC low-density parity-check

LLR log-likelihood ratio

LTE long term evolution

MAC medium access control

MAP maximum a posteriori

MIMO multiple-input multiple-output

MRC maximum ratio combining

MUD multi-user detection

NCDP network-coded diversity protocol

OFDM orthogonal frequency division multiplexing

p.d.f. probability density function

PNC physical layer network coding

PLR packet loss rate

p.m.f. probability mass function

RA random access

RLNC random linear network coding

r.v. random variable

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SA slotted Aloha

SC selection combining

SIC successive interference cancellation

SN slot node

SNR signal to noise ratio

SNIR signal to noise plus interference ratio

SSA spread spectrum Aloha

TDMA time division multiple access

TWRC two-way relay channel

UN user node

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1

Introduction and System Model

Ever since their introduction in 1970 by Norman Abramson, the core principles of random access (RA) have changed little. The intuition pioneered by the Aloha protocol [2] of letting users share a channel in an uncoordinated fashion has proven indeed to be an effective way – when not the only possible one – to exchange data in several situations of practical interest. In fact, the simple idea of RA plays a role in most of the communications standards used today, including wired networks as well as cellular, ad-hoc and satellite systems.

Such a broad range of applications has triggered over the years a lot of interest, leading to countless new protocols that range from variations of Aloha to new approaches that enhance RA performance by leveraging additional features or ideas (carrier sense-based schemes being just one relevant example). The design of novel schemes has in turn been flanked by remarkable research efforts aimed at identifying the ultimate performance limits and potential of such an apparently simple approach to medium access. From this viewpoint, while many fundamental results have been derived over the years, several challenges remain open, among which a final characterisation of the capacity as well of the stability region for a RA system.

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Even a partial review of all the relevant facets of RA would deserve a monograph of its own, and goes well beyond the focus of this volume. We refer the interested reader to the vast literature of excellent books, e.g., [38, 7], and technical papers such as [25] as well as the special issue of the *IEEE Transactions on Information Theory* published in March 1985 [51].

In this work, instead, we mainly address a specific family of schemes proposed in the past few years, which we label as *modern* RA protocols. The background for these solutions dates back to the idea devised by Choudhury and Rappaport in 1983 with Diversity Aloha [11]: modify the basic RA approach by letting users transmit multiple copies of their data over the shared medium, in the hope that at least one of them will be retrieved at the destination despite the increased channel load. Modern schemes, however, take a fundamental step forward in the use of this principle by applying on top of it advanced signal processing and detection techniques (e.g., multi-user detection and successive interference cancellation (SIC)) which became practical during the past three decades. As we will extensively discuss, combining these with diversity can significantly boost the performance of RA, making it competitive to coordinated access protocols and thus further extending its applicability.

An essential enabler for this blend has been the development of digital architectures capable of buffering large amounts of signal samples. Together with a steady increase in computational speed, this allowed to iteratively apply complex signal processing algorithms on the stored samples. As a result, as soon as a packet is retrieved, a receiver may be capable of effectively removing the interference contribution of the successful user from the overall incoming signal, and attempt decoding of other previously corrupted transmissions in an iterative fashion. The first examples of application of these principles lie in the area of spread spectrum communications, where several excellent references can be found to both understand the key features and implementation challenges that have to be faced for SIC to work in practical systems [40, 39, 64, 83, 24, 5, 67, 33, 73].

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On the other hand, the seminal mapping of these ideas to the design of RA protocols dates back to 2007 with the contributions of Casini, Del Rio Herrero and De Gaudenzi [8] as well as of Yu and Giannakis [84]. These works showed how advanced signal processing techniques could indeed lead to dramatic improvements, and ignited a revived interest towards Aloha-based protocols and their use for a whole class of high-throughput and high-reliability applications that were up to that moment precluded to them.

In this monograph, we explore some of these modern RA schemes, highlighting their key working principles, potential and performance drivers. In the spirit of a tutorial work, we often abstract implementation details, referring the reader to dedicated books and research articles available in the literature. We try, instead, to offer an introduction to some analytical tools that can be used to model and understand the behaviour of the considered protocols. After having introduced a general system model in § 1.1 and revisited some theoretical bounds for the RA channel in Chapter 2, we dedicate Chapter 3 to protocols that extend the original slotted Aloha leveraging SIC and other advanced techniques such as physical layer network coding. Complementarily, Chapter 4 offers a glance on unslotted systems, for which, despite their conceptual simplicity, a comprehensive performance model for modern RA protocols is still elusive. Finally, in Chapter 5 we introduce a different class of schemes that exploit the availability of multiple receivers to improve the performance of slotted Aloha via spatial diversity.

1.1 Framework and System Model

As common practice in tutorials and original scientific works, we rely on some simplifying assumptions for the system model, both for the sake of clarity and to highlight some key aspects of the considered access protocols. Given the variety of approaches discussed in this monograph, a unified framework is in general not viable. Yet we identify in this section some common assumptions and modelling features that will serve as a common ground for all the presented schemes. In turn, each chapter will introduce the additional details required to properly model

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the protocol under consideration, and briefly discuss their meaning with respect to practical implementations when relevant.

Throughout our discussion, we assume a very large (possibly infinite) population of users, or *terminals*, that transmit packets over a shared wireless channel to a common receiver. All data units contain nR information bits that, after channel encoding with rate R and modulation, are sent on the medium as bursts[1] of duration $T_{\mathsf{p}} = nT_s$ seconds, where T_s is the symbol time.

We do not rely on any specific geometry for the user topology, and assume perfect power control, so that bursts of different users arrive at the receiver with the same power level. Accordingly, no capture effect is considered [70, 85], and we further assume that, unless otherwise specified, no multi-user detection (MUD) capabilities are available.[2] Thus, whenever two or more bursts collide at the receiver none of them can be decoded unless interference cancellation is implemented. In turn, such procedure can take place only if the receiver has knowledge about one of the colliding bursts, as will be extensively discussed in Chapter 3. This set of working hypotheses is especially relevant and quite common for slotted systems, and is often referred to as a *destructive collision* model. Further details on additional channel assumptions as well as on the decoding model at the receiver will be provided when introducing specific RA schemes, in an attempt to keep the analytical framework as simple as possible and focus on the key protocol design tradeoffs.

From a medium access control (MAC) perspective, the monograph will concentrate in particular on extensions of the Aloha paradigm [2], having terminals transmit a packet over the channel as soon as it is generated and without implementing distributed coordination strategies such as, e.g., carrier sensing. Two families of schemes will be considered, covering both a scenario in which transmitters can rely on some level of synchronisation provided by the receiver, and the case of users being completely uncoordinated. In the former setup, terminals send their packets in instants chosen such that each burst falls within

[1] The terms *packet* and *burst*, as well as *user* and *terminal* will be used interchangeably throughout the text.

[2] A relevant exception to this will be presented in details in Chapter 3.2, where physical layer network coding techniques will be explored.

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the boundaries of a predetermined time interval at the receiver, giving birth to the well-known family of *slotted* systems. Conversely, when no form of synchronism is shared among users, *unslotted* RA takes place, possibly leading to partial overlaps or collisions of packets at the receiver.

Given the different nature of the schemes that will be discussed, it would be impractical to provide a unique formulation of the quantities used to evaluate the system performance. As a common ground, however, we refer to the number of users that access the channel over a reference time interval as the load, and model it for asymptotically large populations as a Poisson random variable (r.v.) of parameter G. From this viewpoint, we assume that no feedback from the receiver nor retransmission policies are in place, focusing on networks that are intrinsically stable [7]. Under these assumptions, we characterise the system behaviour mainly in terms of two metrics. The first one is the throughput S, which captures the average number of information units successfully recovered by the receiver over a reference time interval, and represents a typical performance indicator for modern RA protocols. The second and complementary metric is the packet loss rate (PLR), defined as the probability for a user that accessed the channel not to be correctly decoded at the receiver. The PLR is especially relevant for the broad set of applications that employ uncoordinated access in low load conditions, such as logon procedures in satellite or terrestrial networks, which have stringent requirements in terms of reliability. Once more, the aforementioned definitions will be clarified and instantiated in detail throughout the monograph.

Full text available at: http://dx.doi.org/10.1561/1300000047

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