

NPS-EC-02-004

NAVAL POSTGRADUATE SCHOOL



LITERATURE SEARCH AND REVIEW of the Impact of Noise on Wireless Communications

Prepared for:
Federal Communications Commission
Washington, DC

March 2002

By
Wilbur R. Vincent
George F Munsch
and
Richard W. Adler

Approved for public release: distribution is unlimited

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503.

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
March 2002

3. REPORT TYPE AND DATES COVERED
Literature Survey

4. TITLE AND SUBTITLE
LITERATURE SEARCH AND REVIEW
of the Impact of Noise on Wireless Communications

5. FUNDING NUMBERS

6. AUTHOR(S)
Vincent, Wilbur R.; Munsch, George F.; and Adler, Richard W.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Signal Enhancement Laboratory
Department of Electrical and Computer Engineering
Naval Postgraduate School
Monterey, CA 93943-5000

8. PERFORMING ORGANIZATION
REPORT NUMBER
NPS-EC-02-004

SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Federal Communications Commission
Washington D.C.

10. SPONSORING / MONITORING
AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

The views expressed in this thesis are those of the authors and do not reflect the official policy or position of the Department of Defense, The Federal Communications Commission, or other U.S. Government agency.

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (*maximum 200 words*) A comprehensive review of the literature of radio noise and its impact on wireless radio devices was undertaken. Early in the effort it was apparent that pertinent mathematical models of radio noise had been formulated by Dr. David Middleton. Thus, Dr. Middleton's work is featured in Section 1 of the report. In addition, the abstracts and/or text of more than 100,000 documents were reviewed by access to on-line libraries and by visits to special libraries. Because of the massive amount of pertinent material found, it was necessary to divide the results into convenient sections.

14. SUBJECT TERMS
Wireless LANs, radio noise, radio interference, UHF Noise, microwave noise

15. NUMBER OF
PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
Unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT
Unclassified

20. LIMITATION OF ABSTRACT
UL

PREFACE

Wireless communications systems are widely deployed in the unlicensed bands where they share spectrum space with other communications services and with emissions from Industrial, Scientific, and Medical (ISM) devices. It soon became apparent that interference from existing devices and other wireless radio systems using the available unlicensed bands is a primary factor limiting the widespread implementation of wireless radio. This limitation was the topic of discussion and concern by the Technology Advisory Council (TAC) of the Federal Communications Commission in the year 2000, but solid factual information was not available to document the situation.

Under the leadership and guidance of the TAC, a fund was raised by the industrial components of the TAC to conduct a literature search for pertinent documents and information about the radio noise in the bands of interest. This search included a survey of mathematical models of noise applicable to the wireless-radio problem.

Mr. George Hagn (retired from SRI International and a scientific consultant) organized a group of experienced professionals who were already investigating similar radio-noise problems to conduct an extensive search of the available literature. He enlisted the aid of Dr. David Middleton, a widely-recognized international authority on noise models, to participate in the program and the Naval Postgraduate School, Monterey, CA to conduct the literature search and administrative aspects of the effort. Shortly after the start of the program, Mr Hagn suffered serious medical problems that prevented him from further participation in the effort. His duties were assumed by other participants in the program including Professors Richard W. Adler and Wilbur R. Vincent of the Naval Postgraduate School, and a coworker in radio-noise investigative work, Mr. George F. Munsch. This document is the end result of the effort.

A large amount of pertinent material about radio-noise models was provided by Dr. David Middleton, and more complementary material was uncovered during a large-scale literature search effort. The literature search was feasible (and low in cost) because of the availability of excellent on-line libraries. In addition, excellent assistance was obtained from Dr. Robert Hunsucker (the editor of the URSI associated journal, *Radio Science*, whose material is not available on-line). Dr Hunsucker made his library and personal files on radio noise available to us. Additional assistance was provided by Mr. Robert Matheson of the Institute of Telecommunications Sciences (ITS) who assisted us in obtaining access to ITS and other on-line documents.

Of special importance in conducting the library search was the ability to obtain access to a massive amount of on-line material through a reliable and wide-band connection to the Internet. Of special help was the on-line library of the Institute of Electrical and Electronic Engineers EEE (IEEE Explore) and the INSPEC listings. Access to these on-line services greatly reduced the time and cost of conducting the literature-review task and made such an effort feasible.

TABLE OF CONTENTS

PREFACE	i
CONTENTS	ii
INTRODUCTION	iii
Section 1: SELECTED BIBLIOGRAPHY AND REFERENCES OF PHYSICAL NOISE MODELS	1
Section 2: NOISE MEASUREMENTS	37
Section 3: ADDITIONAL INFORMATION ABOUT NOISE MODELS	81
Section 4: NOISE PROPAGATION	91
Section 5: SPECTRUM PLANNING	177
Section 6: SYSTEM MODELS	209
Section 7: MEASUREMENT INSTRUMENTATION	367
Section 8. DISCUSSION	377
Appendix: EXAMPLES OF SIGNALS AND NOISE IN THE 2.4 GHz BAND	383

INTRODUCTION

All participants in the program took part in the search for pertinent publications on radio noise. While this search was directed at the identification of documents on radio noise as it affects wireless radio systems, many radio-noise documents are of general interest and have general applications regardless of the frequency band or application of concern. Thus, considerable judgement was required in the selection of documents to enter into the survey and which to eliminate from the survey.

All references selected for the library were entered into a master file in the EndNote program. This program provided a means to obtain a uniform presentation of each entered document. Abstracts, if available, were included in the listings. In a few cases where a document did not contain an abstract, but the document was available, a brief note was added to the listing. Standard on-line reference numbers such as the INSPEC and other access numbers are included to aid any interested reader to obtain the full text of a document.

A massive amount of radio-noise material was located in the various on-line libraries used during the survey and at the other facilities available to the participants in the program. Because of the large number of documents located during the literature survey, it was necessary to divide the material into subtopics related to radio noise. The EndNote program provided a means to sort the documents into subtopics. These subtopics are organized into sections where each section provides a listing of documents fitting the section title. In some cases a particular document provided material of interest to two or more sections. Such documents were placed in the section best describing their primary topic. A brief introduction is provided at the start of each section.

Because noise models are of interest and use in planning for the effective performance of wireless radio systems, **Section 1** is devoted to that topic. Dr. David Middleton, a specialist in radio noise models, provided an excellent summary of his work and the work of some of his close associates.

Section 2 provides a listing of all documents located with information about radio noise data that is of interest to wireless radio systems.

Section 3 provides documents with additional information about noise models. In general, these documents are directed at more limited aspects of noise models than the more universal models described in Section 1.

Section 4 covers specialized information about the propagation of radio signals and noise from its sources to a victim receiver.

Section 5 identifies several documents that fit into a long-range planning topic.

Section 6 provides a collection of documents describing performance models of various communications systems. This section was included because it contains a large amount of information about the performance of various signal-modulation and signal-detection systems, and the impact of various kinds of noise on these systems.

Section 7 describes possible measurement system configurations that can be used to obtain data and information about the levels and characteristics of noise in bands of interest to wireless radio systems. Several instrumentation configurations are presented along with a discussion of the advantages and disadvantages of each.

Section 8 provides a discussion of the implications and the results of the study.

Lastly, an Appendix provides the results of an investigation into characteristics of signals and noise appearing at the input terminals of a specific 2.4-GHz wireless radio receiver. The measurements were made at the office of one of the participants in the study. The data obtained was used to better understand the characteristics of signals and noise at this location, and to evaluate the impact of the existing radio environment on the operation of one additional wireless device. The measurements clearly indicate that wireless radio devices are rapidly occupying the 2.4 GHz band.