The WAVE Solution – Coming Soon to a Car Near You: Wireless Access

Dr. Guillermo Acosta
Professor Roberto A. Uzcategui

Introduction

The OSI Reference Model

- OSI: Open Systems Interconnection.
- Abstract description of a layered computer network.
- Divides network architecture into seven layers: Application, Presentation, Session, Transport, Network, Data Link, and Physical.

  $\Rightarrow$ Also known as *The Seven Layer Model.*
- More historic and didactic than currently archetypal.
  - Excellent place to start studying network architecture, even though actual systems might not easily fit the model.
  - Most widespread network architecture (TCP/IP) does not fit Seven Layer Model (it has five layers).

The OSI Reference Model (cont.)

- Each layer in one network node communicates with the same layer in another node.
- Each layer serves the layer above it (except the highest) and uses the services of the layer below it (except for the lowest).
- Layers are functionally specified through protocols
- Protocols
  - Conventions or standards that govern the syntax, semantics and timing of communication between entities.
  - May be implemented in hardware, software or a combination of both.
  - In software, more concerned with syntax and semantics.
  - In hardware, more concerned with behavior of devices (including timing) and characteristics of signals.

The Seven Layers

- Application

  Interacts with the communication software, which is outside the scope of the model
- Presentation

  Translates the different syntaxes and semantics that Application Layers entities may use to a format understood by the Session Layer
- Session

  Establishes, manages, and terminates connections between local and remote computers
- Transport

  Does flow control, segmentation/de-segmentation of data, and error control
- Network

  Transfers data over a network of nodes (routing functions)

  May do fragmentation and reassembly
- Data Link

  Transfers data between adjacent network nodes (one link; no routing involved)

  Controls physical medium access
- Physical

  Defines the signals and physical specs. of the devices, according to the physical medium

The Internet Protocol (IP) Suite

- RFC 1122
- Not an abstract model, but an actual implementation
- Five of the seven OSI layers: Application, Transport, Network (called Inter-Networking), Data Link and Physical (these last two, combined in one called Link)
- Correspondence with the OSI Model not perfect (for instance, a protocol used in IP's Link Layer straddles OSI's Network and Data Link), but we will assume so for didactic purposes

OSI Model

	Unit	Layer	Function	IP Suite	Examples
Host Layers	Data	7. Application	Network process to application	NNTP, SIP, SSI, DNS, FTP, Gopher, HTTP, NFS, NTP, DHCP, SMPP, SMTP, SNMP, Telnet, RIP, BGP	HL7, Modbus
		6. Presentation	Data representation and encryption	MIME, XDR, SSL, TLS	TDI, ASCII, EBCDIC, MIDI, MPEG
		5. Session	Inter-host communication	Sockets. Session establishment in TCP, RTP	NetBIOS, SAP, Half Duplex, Full Duplex
	Segment	4. Transport	End-to-end connections and reliability	TCP, UDP, SCTP	NBF, nanoTCP, nanoUDP
Media Layers	Packet	3. Network	Path determination and logical addressing	IP, IPsec, ICMP, IGMP	NBF, Q.931, IS-IS
	Frame	2. Data Link	Physical addressing (MAC & LLC)	OSPF, PPP, SLIP, PPTP, L2TP	802.3 (Ethernet), 802.11a/b/g/n MAC/LLC, 802.1Q
	Bit	1. Physical	Media, signal and binary transmission		100BASE-TX, POTS, SONET, SDH, DSL, 802.11a/b/g/n PHY

What is WAVE?

- Wireless Access for Vehicular Environments
- Radio communications system intended to provide interoperable wireless networking services for transportation
- Mode of operation for use by IEEE 802.11 devices in environments where the physical layer properties are rapidly changing and where very short-duration communications exchanges are required
- Mode of operation used by IEEE 802.11 devices in the Dedicated Short-Range Communications (DSRC) band allocated for Intelligent Transportation Systems (ITS) communications

Why WAVE?

To provide interoperable wireless networking services for transportation, including

- Those recognized for Dedicated Short-Range Communications (DSRC) by the U.S. National Intelligent Transportation Systems (ITS) Architecture (NITSA)
  - Arterial and freeway management
  - Crash prevention and safety
  - Road weather management
  - Roadway operations and maintenance
  - Transit management
  - Traffic incident management
  - Emergency management
  - Electronic payment and pricing
  - Traveler information
  - Information management
  - Commercial vehicle operations
  - Intermodal freight
- Many others not specifically identified in the architecture
  - Ecommerce
  - Internet access

WAVE Takes Place Between…

- Roadside units located within 1000m of each other (in line of sight)
- Roadside units and vehicles (vehicle-to-infrastructure, or V2I) moving at high speed
- Roadside units and vehicles (V2I) moving slowly
- Roadside units and stopped vehicles (V2I)
- Vehicles (vehicle-to-vehicle, or V2V) moving at high speeds (up to 140 km/h)

History

MILESTONE	YEAR
Intelligent Vehicle-Highway Society (IVHS) of America and US DOT collaborate on IVH strategic plan	1992
Intelligent Transportation Society of America (ITSA) and US DOT collaborate on national Intelligent Transportation System (ITS) plan	1995
US DOT searches for frequency band	1995/96
ITSA requests 5.9 GHz	1997
FCC allocates 75 MHz (5.85-5.925 GHz)	1999
Standards effort begins (ASTM)	1999
Technology selection (ASTM)	2003
FCC final report and order licensing	2003
IEEE approves task group 802.11p to prepare a WAVE standard	2004

Why Base WAVE on 802.11?

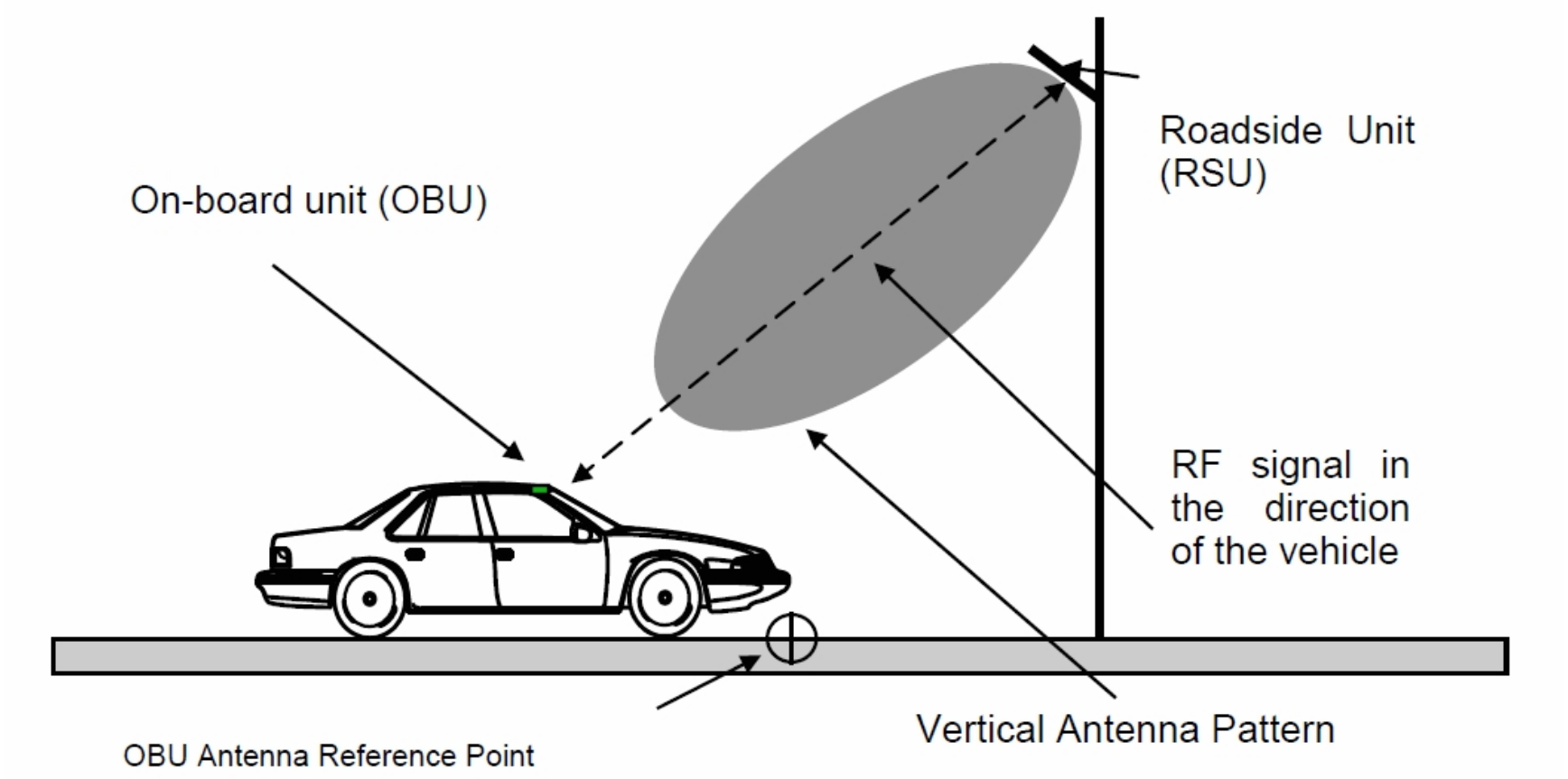
- To have a stable standard supported by experts in wireless technology.
  - Necessary to guarantee interoperability between vehicles made by different manufacturers.
  - Necessary to guarantee interoperability with roadside infrastructure in different geographic locations.
- To guarantee that the standard will be maintained in concert with other ongoing developments in IEEE 802.11.
- Since 802.11p is based o 802.11a, synergies in chipset design are expected to help ensure the necessary production economies of scale.

Why a Different Version of 802.11?

Changes are required to support

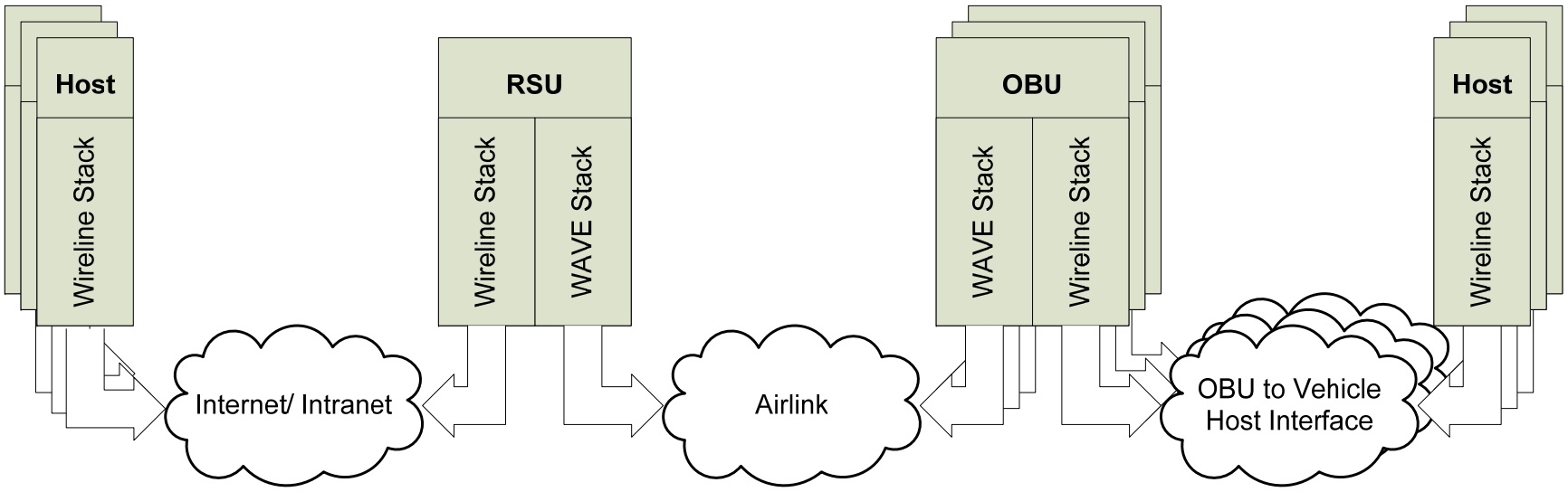
- The longer ranges of operation (up to 1000 m)
- The high speed of the vehicles
- The extreme multipath environment
- The need for multiple overlapping ad-hoc networks to operate with extremely high quality of service
- The nature of the applications to be executed
- A special type of beacon frame, used only in the ITS (DSRC) frequency band

A Simple WAVE System



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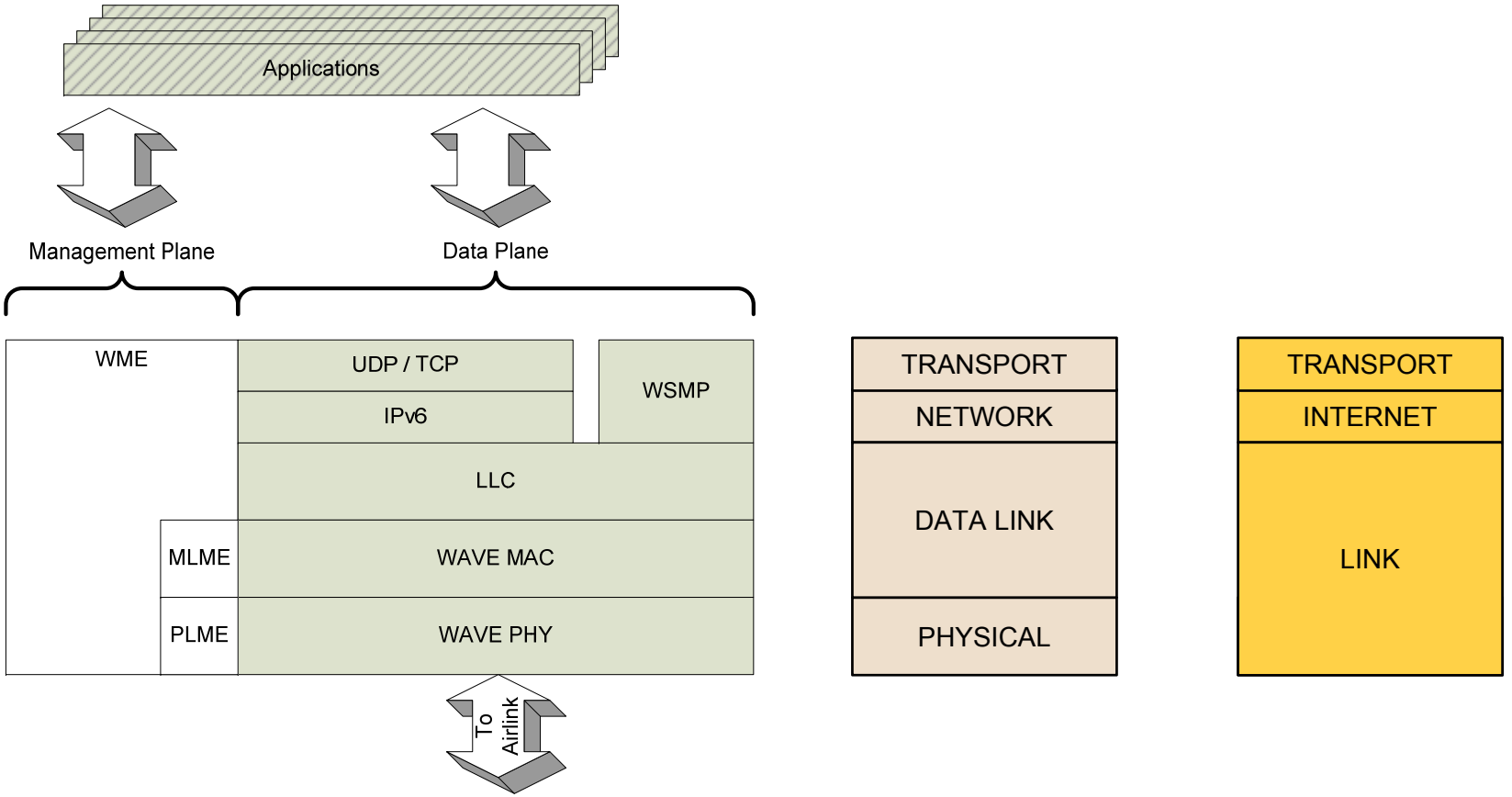
WAVE System Components



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RSU: Roadside Unit *OBU: Onboard Unit*

WAVE Protocol Stack



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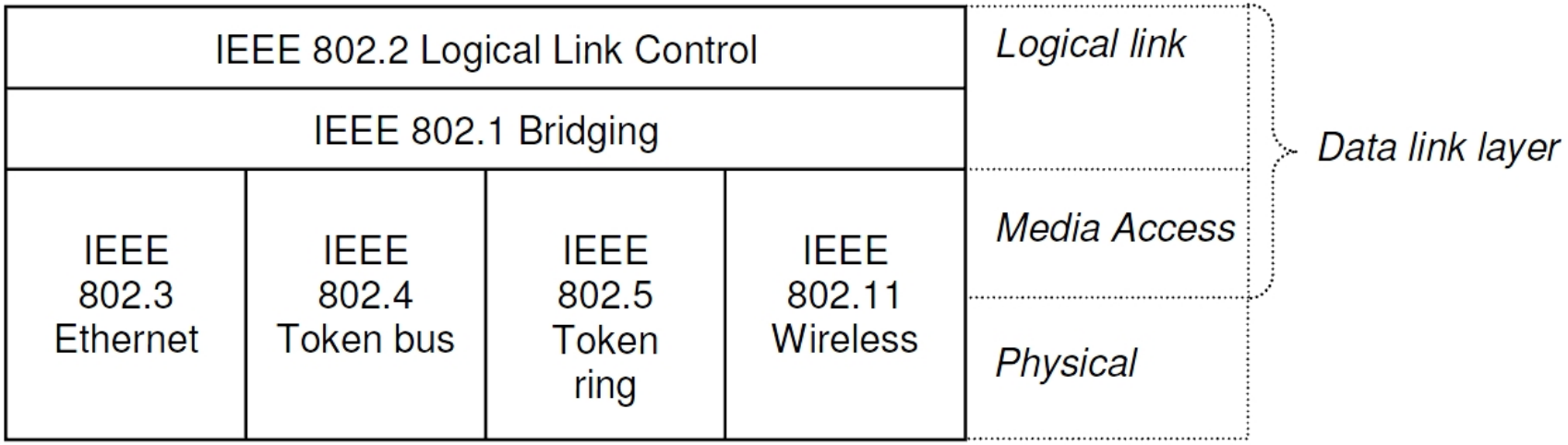
LLC: Logical link control
WME: WAVE management entity
MLME: MAC sublayer management entity
WSMP: WAVE short message protocol
PLME: Physical layer management entity
UDP: User Datagram Protocol

Background

Wired vs. Wireless LANs

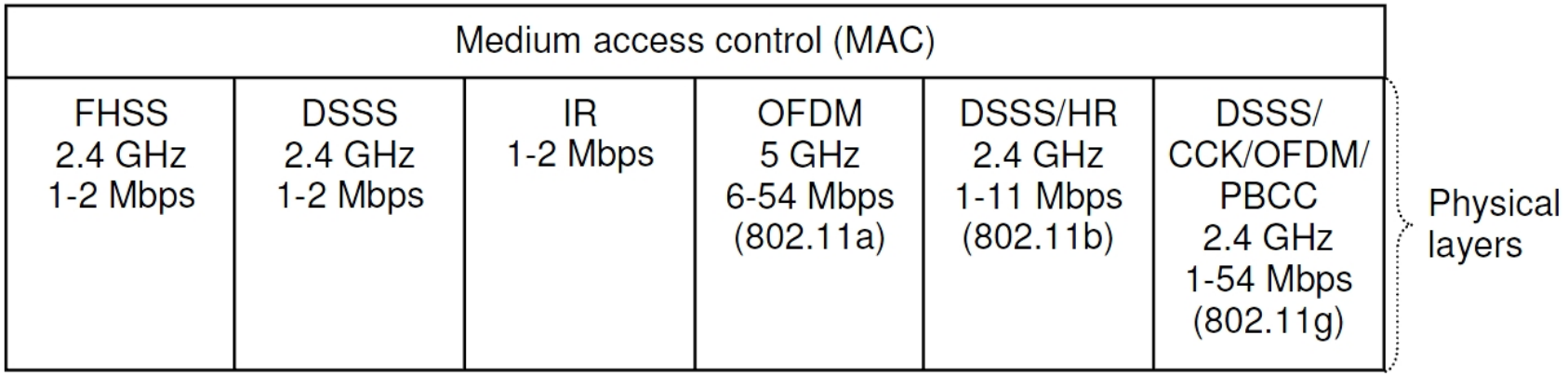
- In WLANs, there is no physical destination location.
- WLANs use a medium that has neither absolute nor readily observable boundaries.
- Signals in WLANs are unprotected from signals from other wireless systems that may be sharing the medium.
- The wireless medium is significantly less reliable than any wire.
- WLANs have dynamic topologies.
- WLAN stations may be “hidden” from each other.
- The wireless medium has time-varying and asymmetric propagation properties.
- Given the lack of precise boundaries of the wireless medium, logically disjoint WLANs can interfere with each other.
- WLANs must deal with mobile stations.
- Mobile stations are usually battery-powered, so power management is an important consideration.

IEEE 802



K. Bilstrup, "A survey regarding wireless communication standards intended for a high-speed vehicle environment," Halmstad University, Halmstad, Sweeden, Tech. Rep. IDE0712, Feb. 2007.

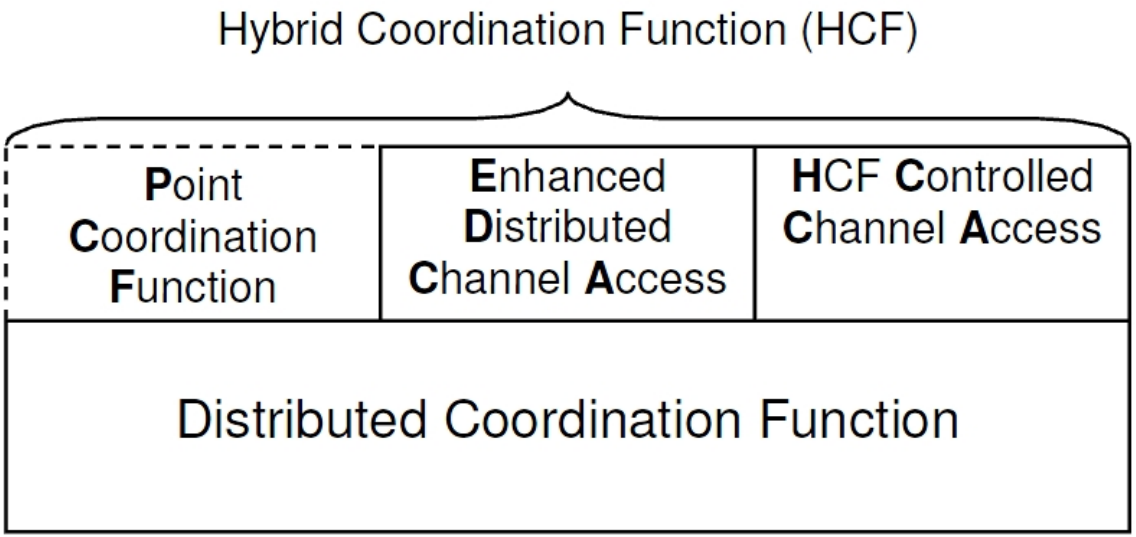
IEEE 802.11



CCK: Complementary code keying *DSSS: Direct-sequence spread spectrum* *FHSS: Frequency-hopping spread spectrum* *HR: High rate*
IR: Infrared *OFDM: Orthogonal frequency-division multiplexing* *PBCC: Packet binary convolutional code*

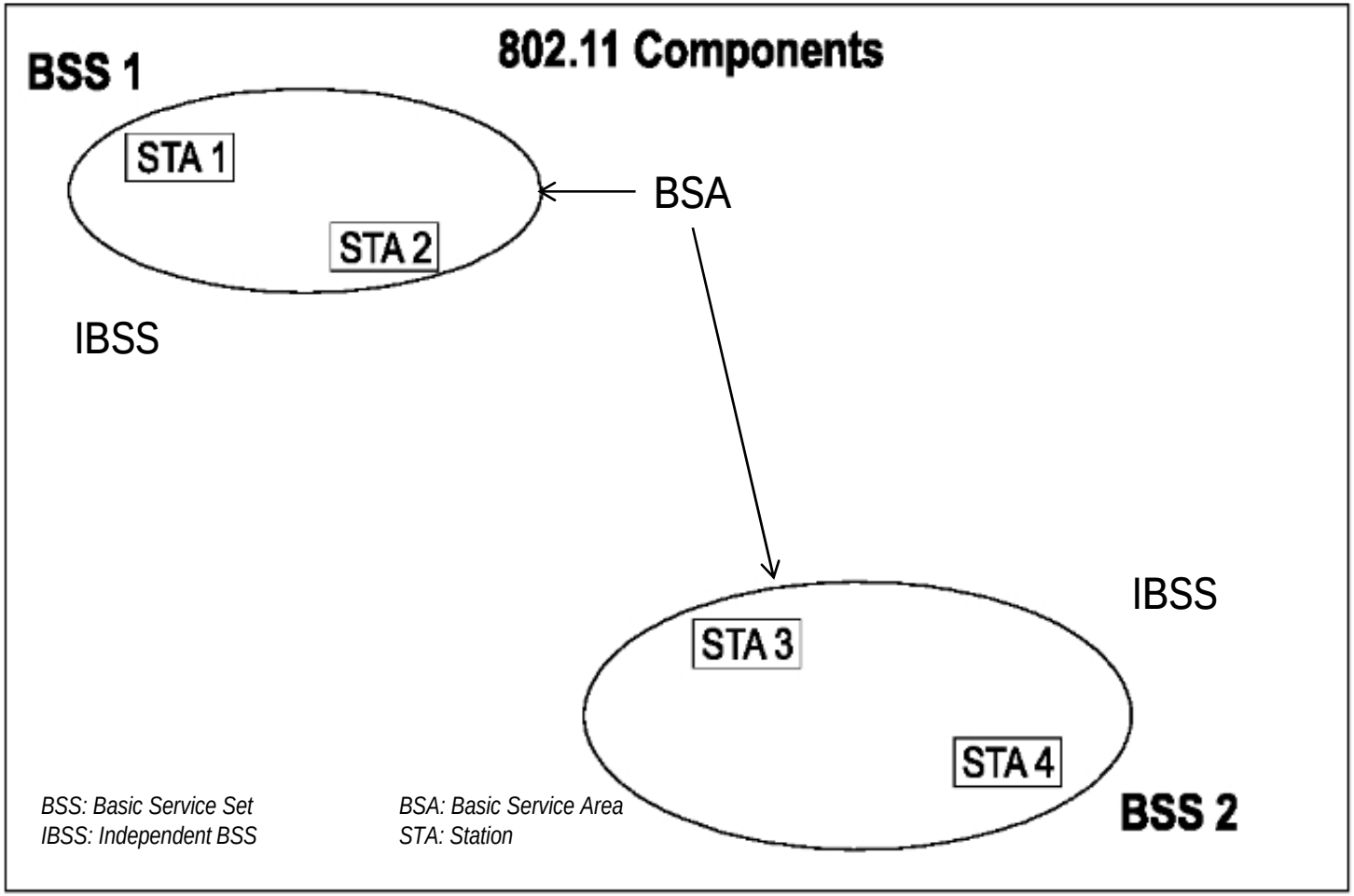
K. Bilstrup, "A survey regarding wireless communication standards intended for a high-speed vehicle environment," Halmstad University, Halmstad, Sweeden, Tech. Rep. IDE0712, Feb. 2007.

IEEE 802.11e (for QoS)



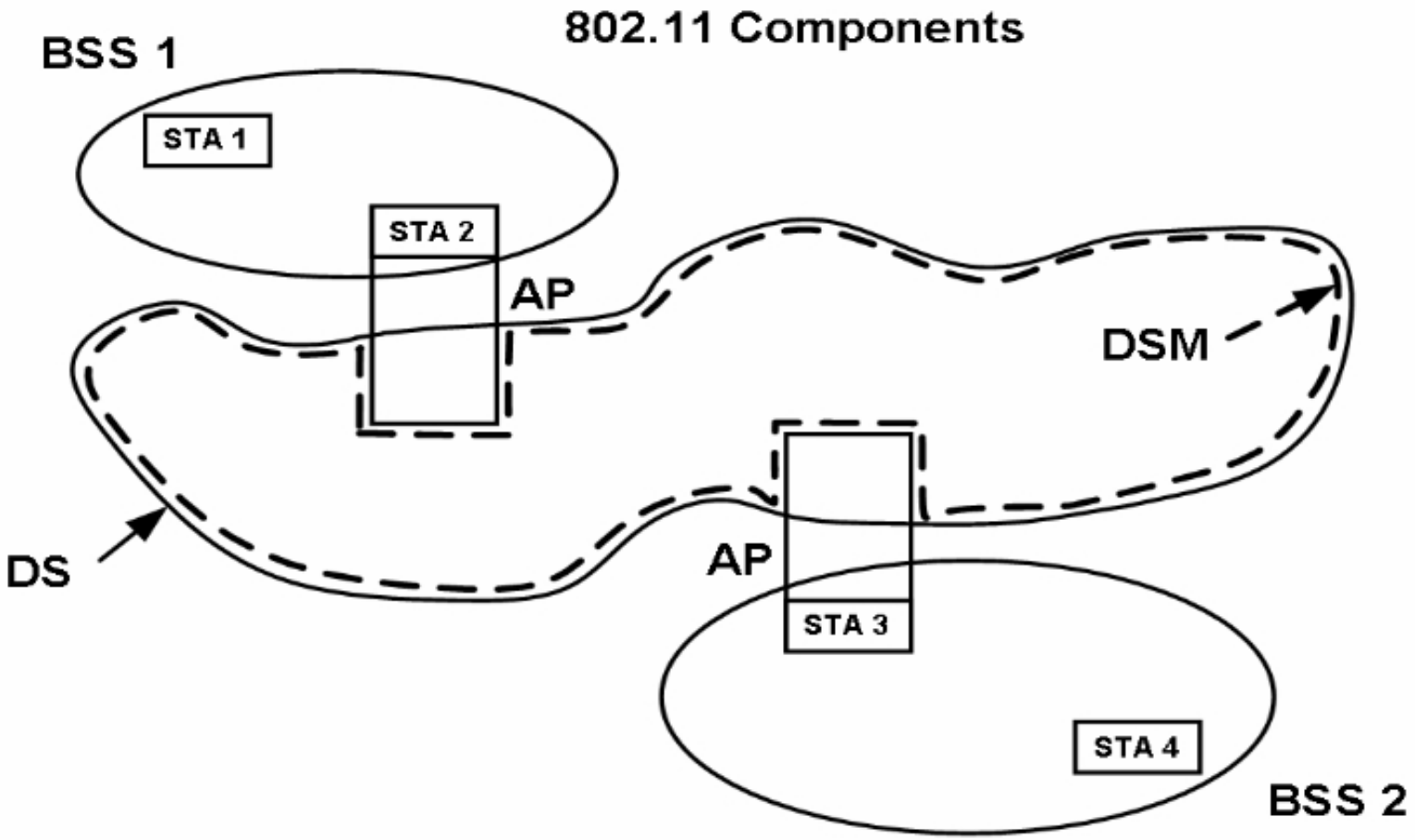
K. Bilstrup, “A survey regarding wireless communication standards intended for a high-speed vehicle environment,” Halmstad University, Halmstad, Sweeden, Tech. Rep. IDE0712, Feb. 2007.

IEEE 802.11 Basic Service Set



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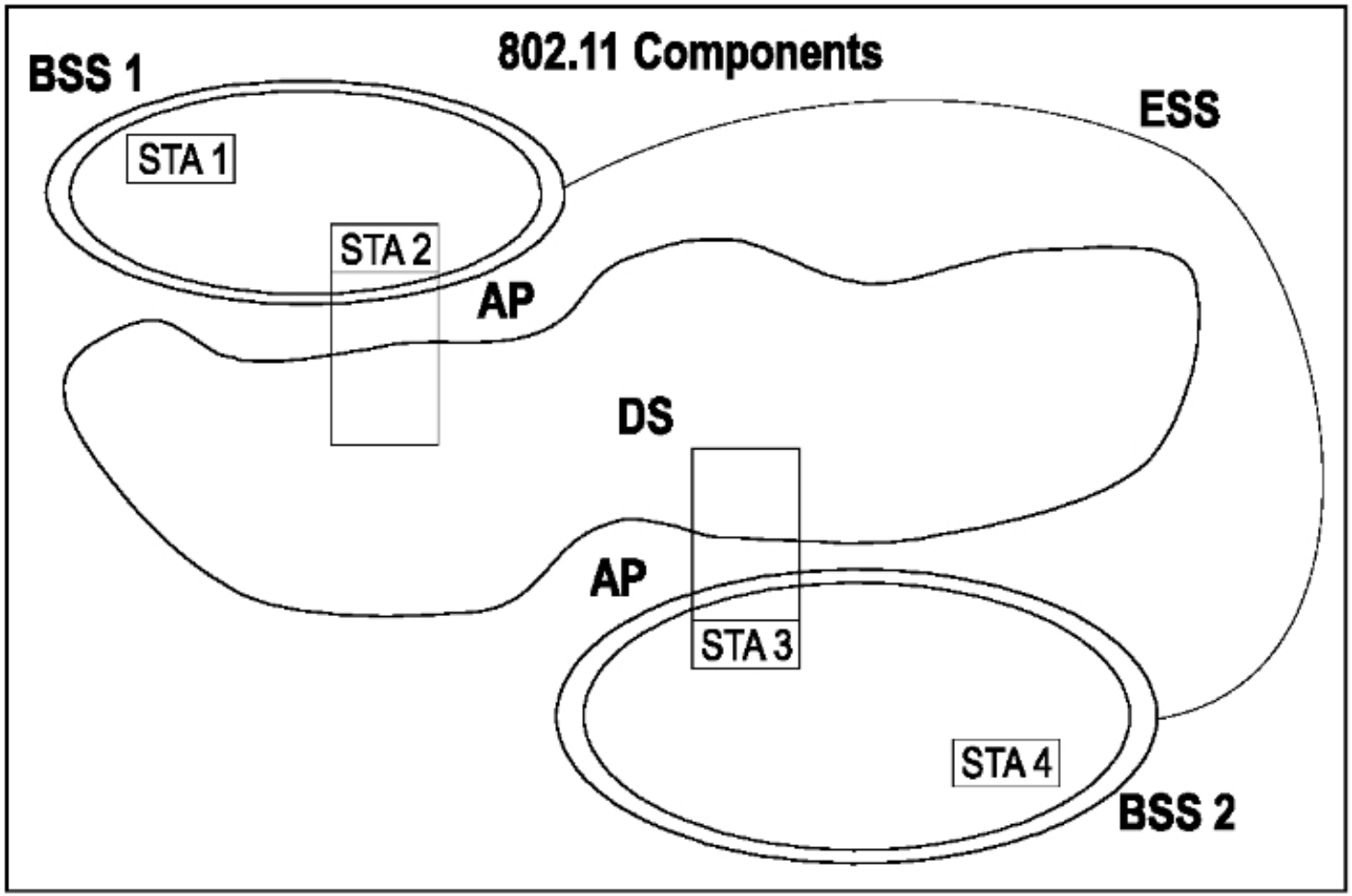
IEEE 802.11 Distribution System



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AP: Access Point *BSS: Basic Service Set* *DS: Distribution System* *DSM: DS Medium* *STA: Station*

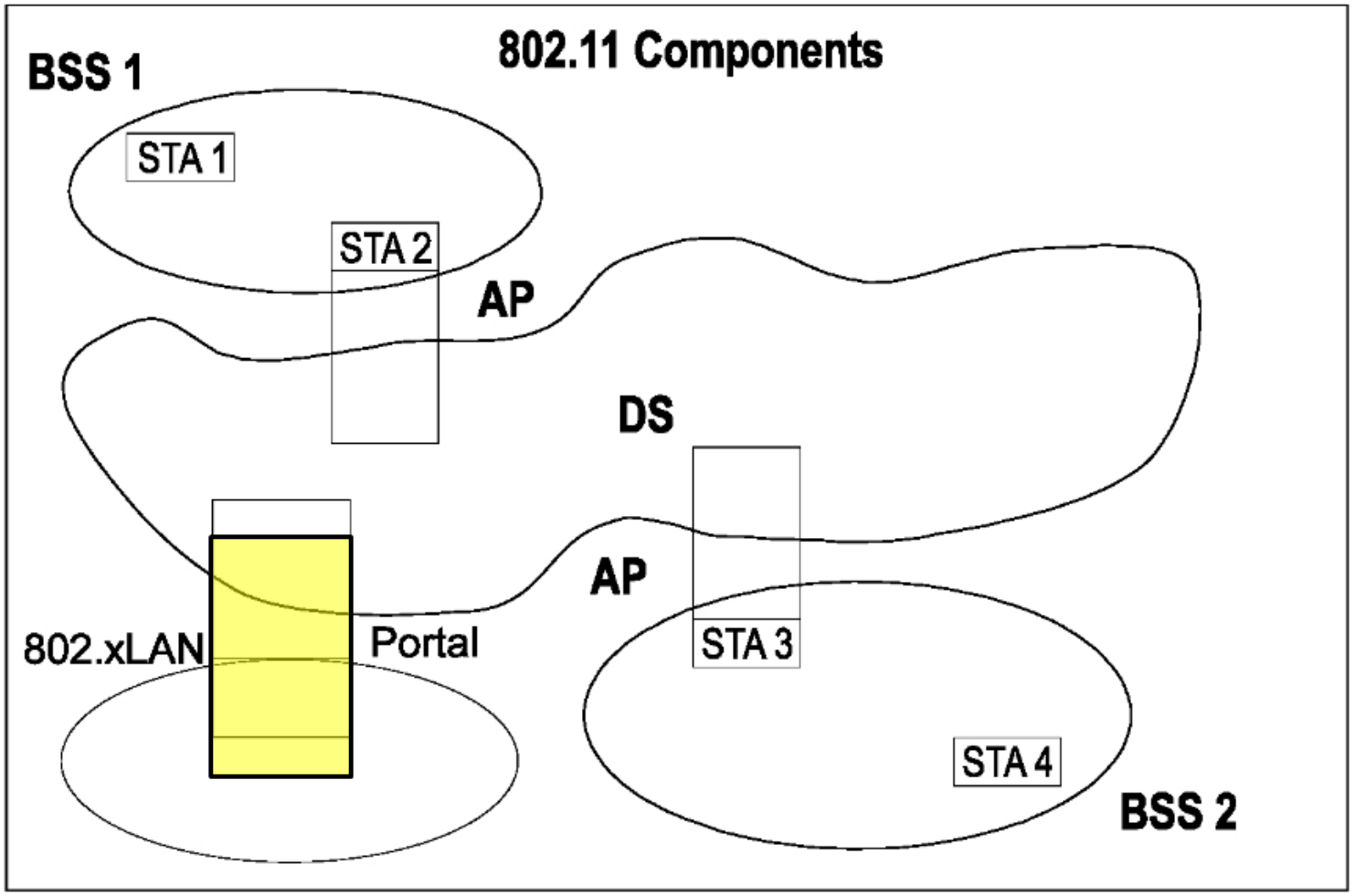
IEEE 802.11 Extended Service Set



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AP: Access point *BSS: Basic Service Set* *DS: Distribution System* *ESS: Extended service set*

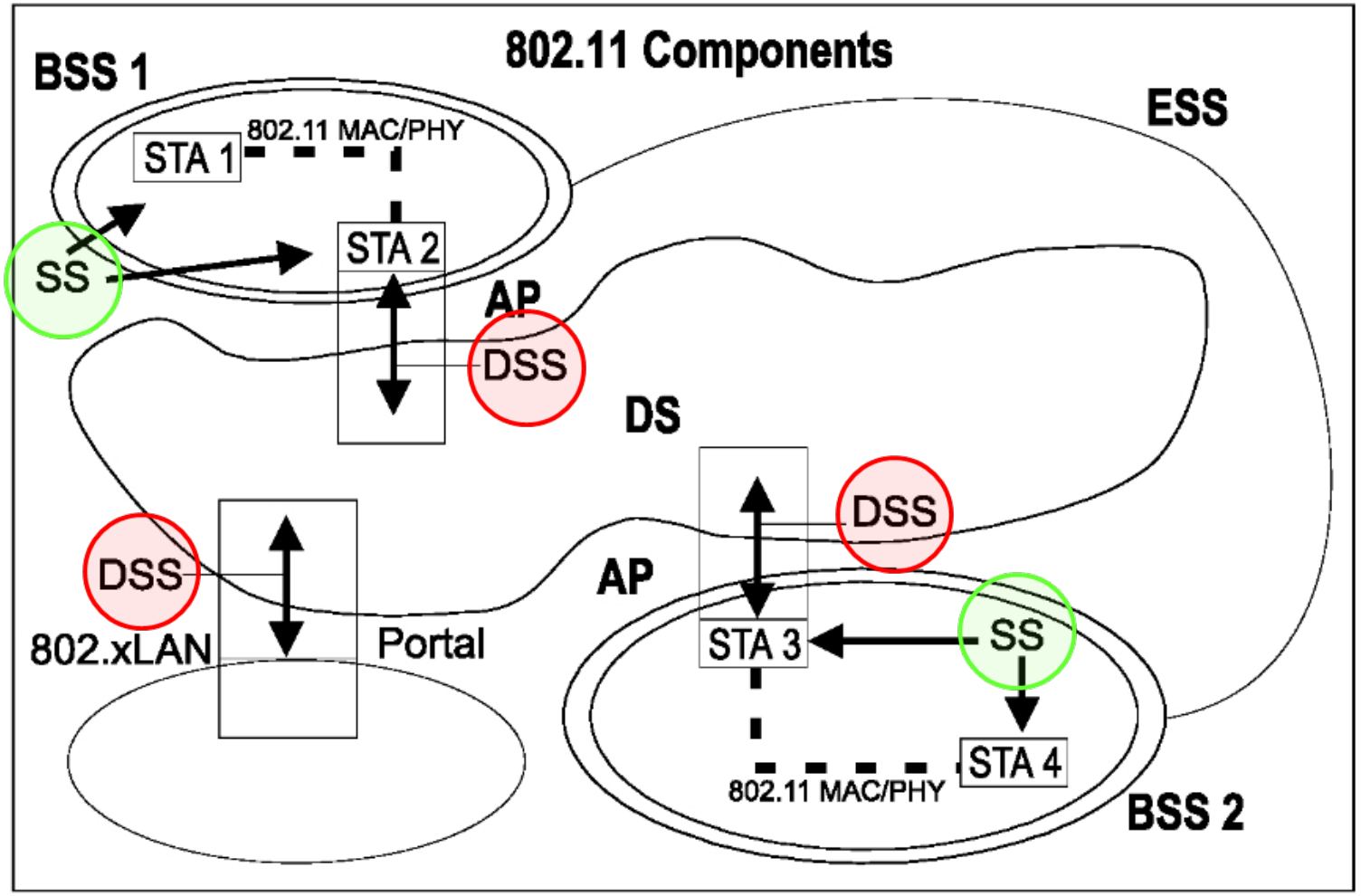
Connection to Wired LAN



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AP: Access point *BSS: Basic Service Set* *DS: Distribution System* *ESS: Extended service set*

Logical Services



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AP: Access point BSS: Basic Service Set DS: Distribution System DSS: DS Service ESS: Extended service set SS: STA service

Logical Services (cont.)

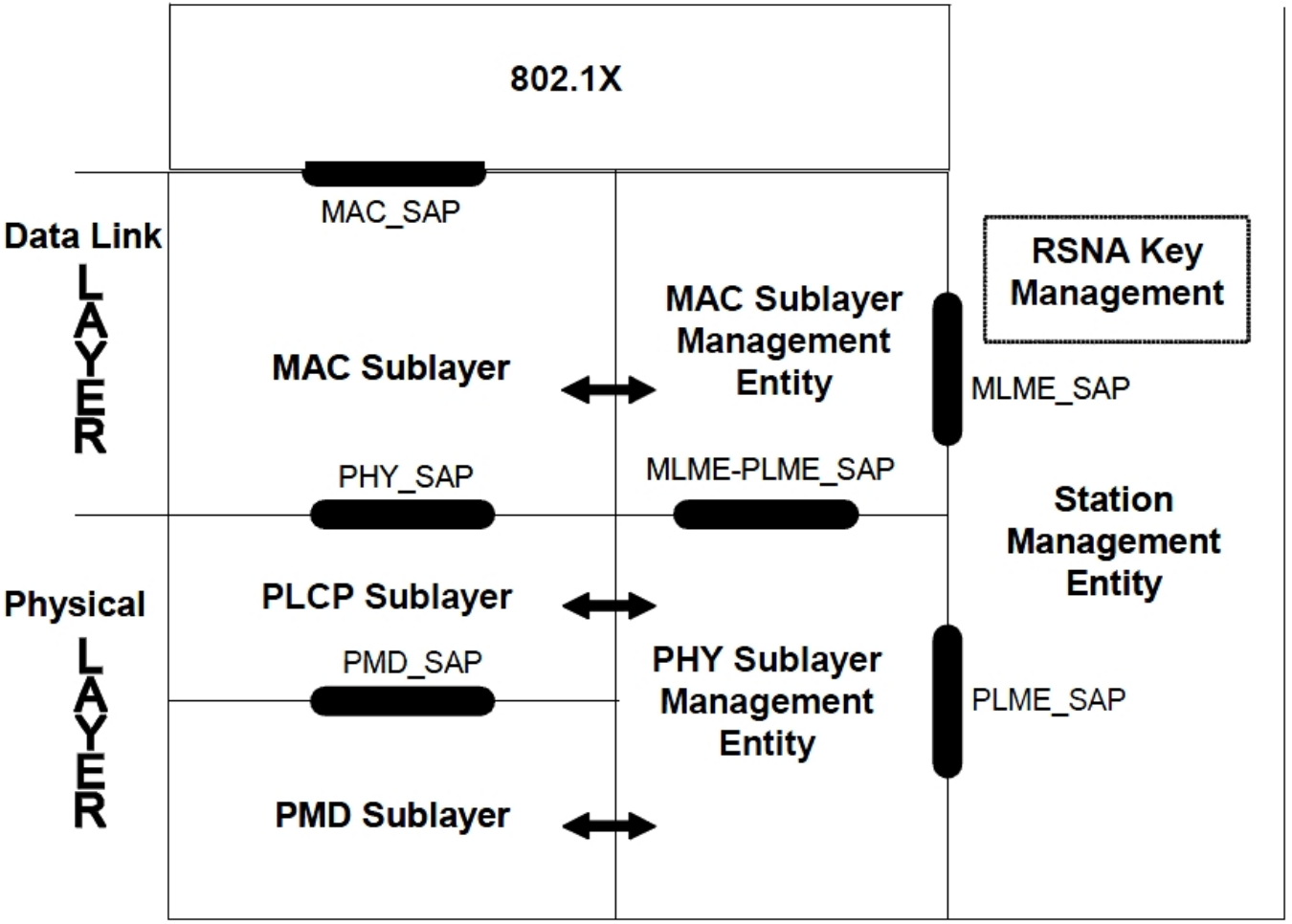
SS: services provided by STAs

- Authentication
- De-authentication
- Data confidentiality
- MAC Service Data Unit (MSDU) delivery
- Dynamic Frequency Selection (DFS)
- Transmit Power Control (TPC)
- Higher-layer timer synchronization
- QoS traffic scheduling

DSS: services provided by the DS

- Association
- Disassociation
- Distribution
- Integration
- Re-association
- QoS traffic scheduling

IEEE 802.11 Reference Model



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MLME: MAC sublayer management entity *PLME: Physical layer management entity* *PMD: Physical medium dependent* *SAP: Service access point*

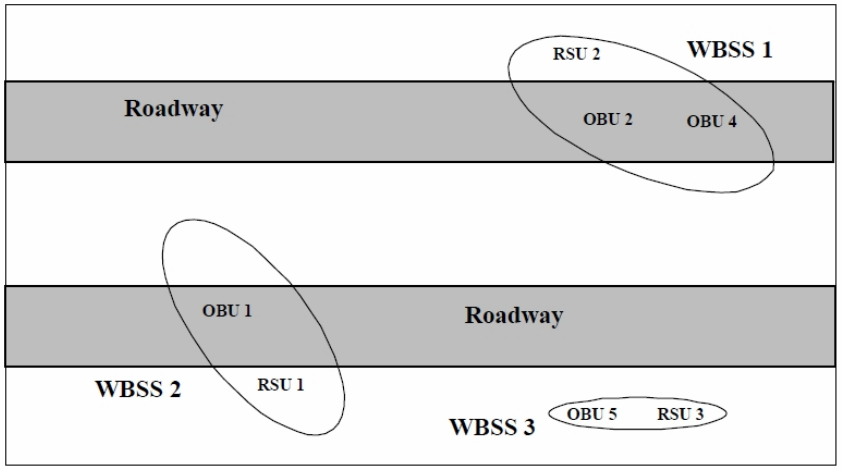
WAVE

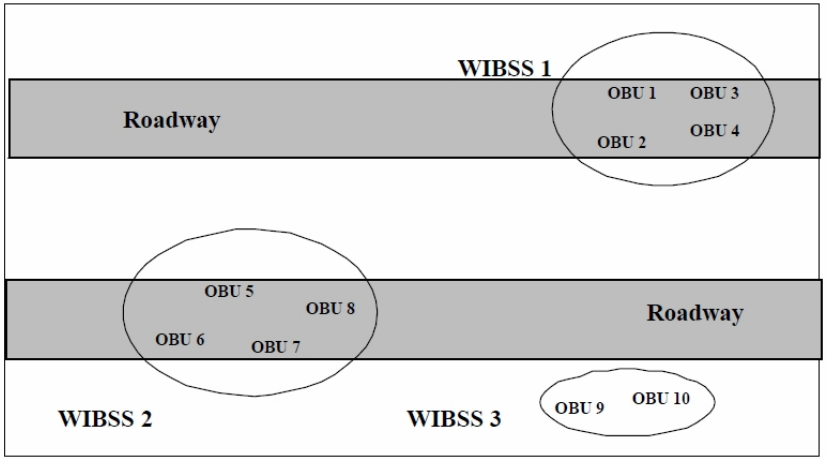
WAVE vs. IEEE 802.11

- Communications in a highly mobile environment
- 10 MHz channels
- One half the data rates of 802.11
- Control Channel and (6) Service Channels
- Unique Ad Hoc Mode
- Random MAC address
- RSSI high accuracy mode
- 16 QAM use in the high speed mobile environment
- Spectral mask modification
- Option for more severe operating environment (automotive)
- Priority control
- Power Control

Wayne Fisher, ARINC, March 2004

WAVE BSS (WBSS)

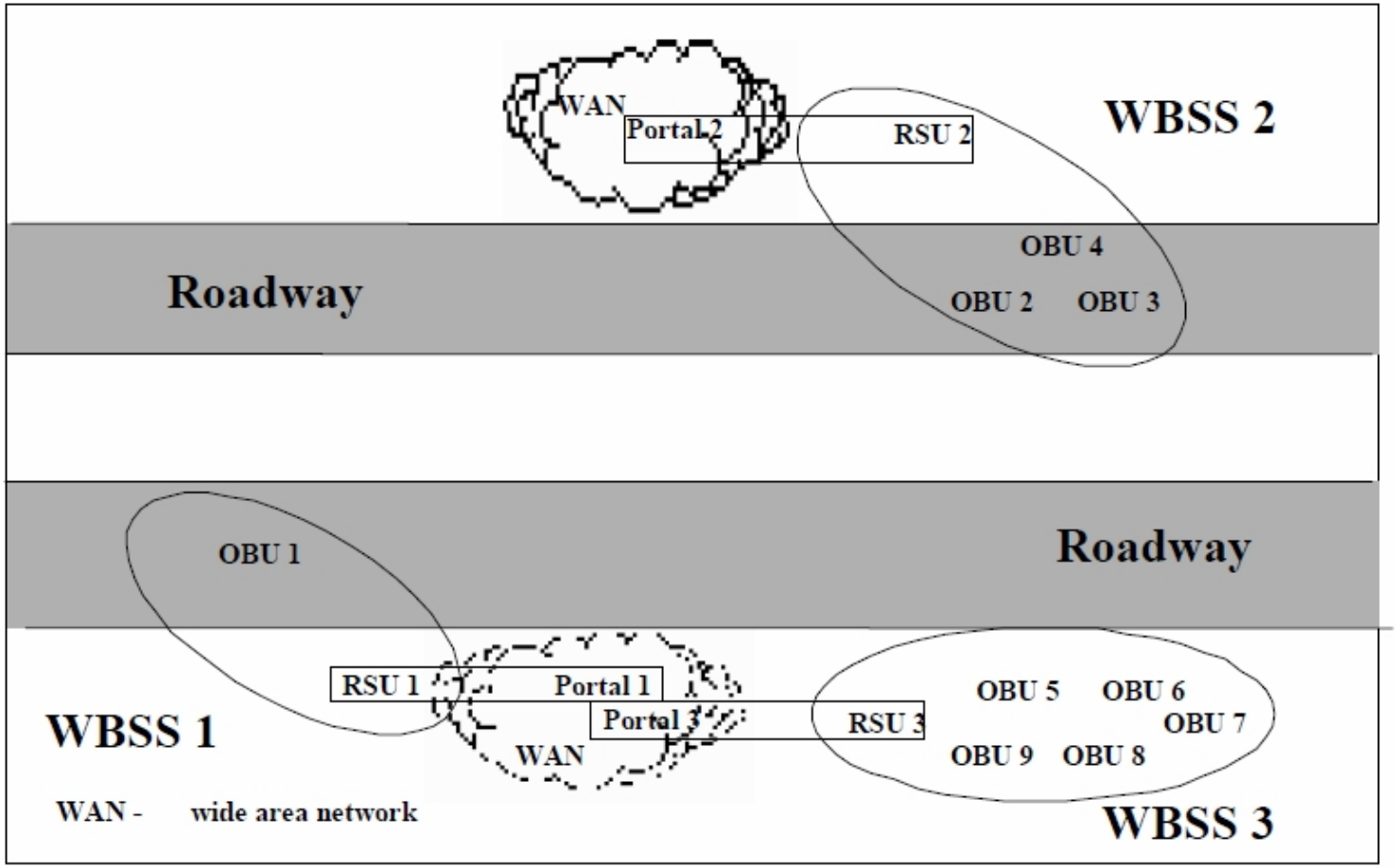




OBU: Onboard unit
RSU: Roadside unit
WBSS: WAVE basic service set
WIBSS: WAVE independent BSS

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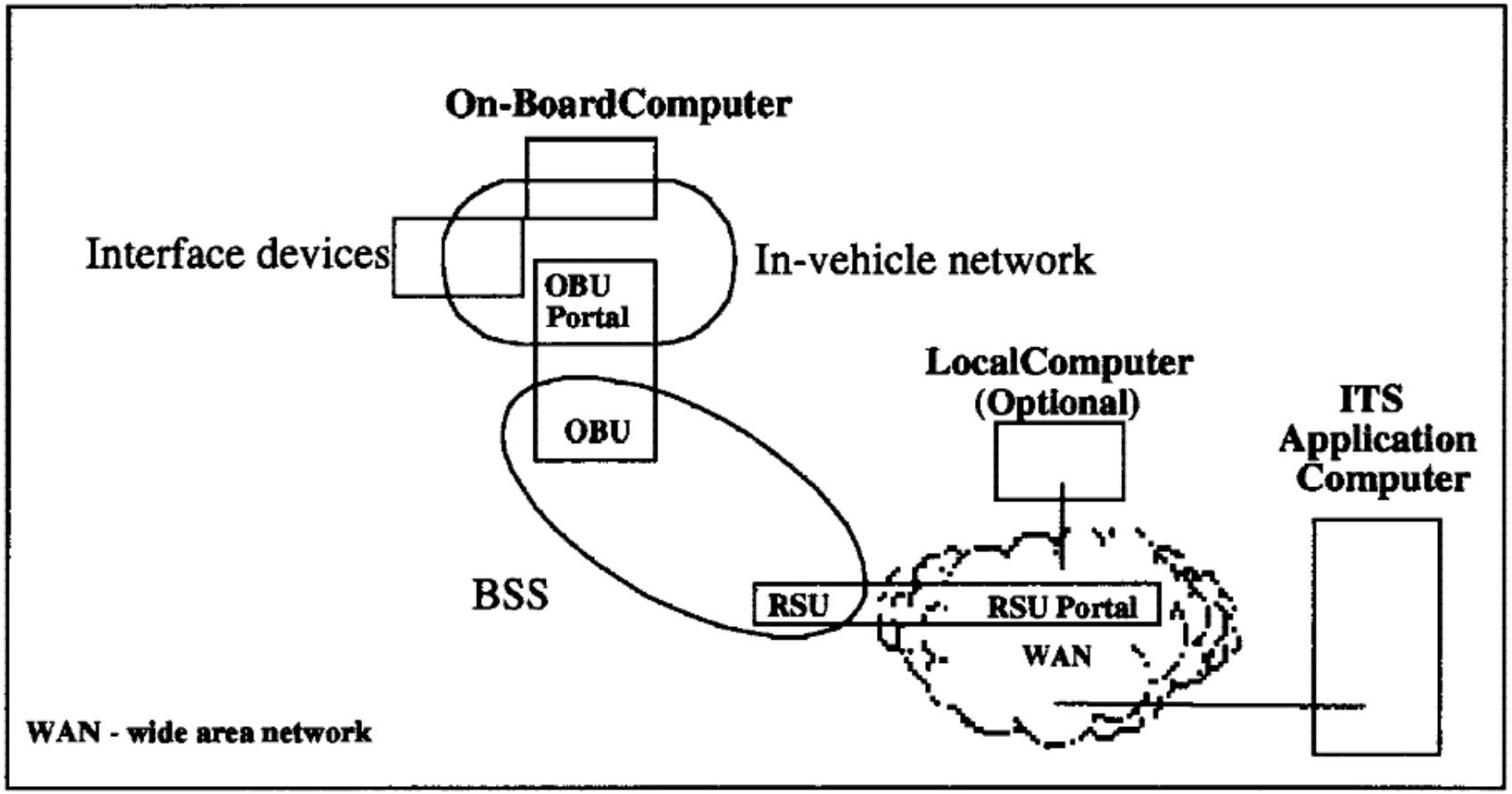
Connection of OBUs to WANs



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OBU: Onboard unit *RSU: Roadside unit* *WAN: Wide area network* *WBSS: WAVE basic service set*

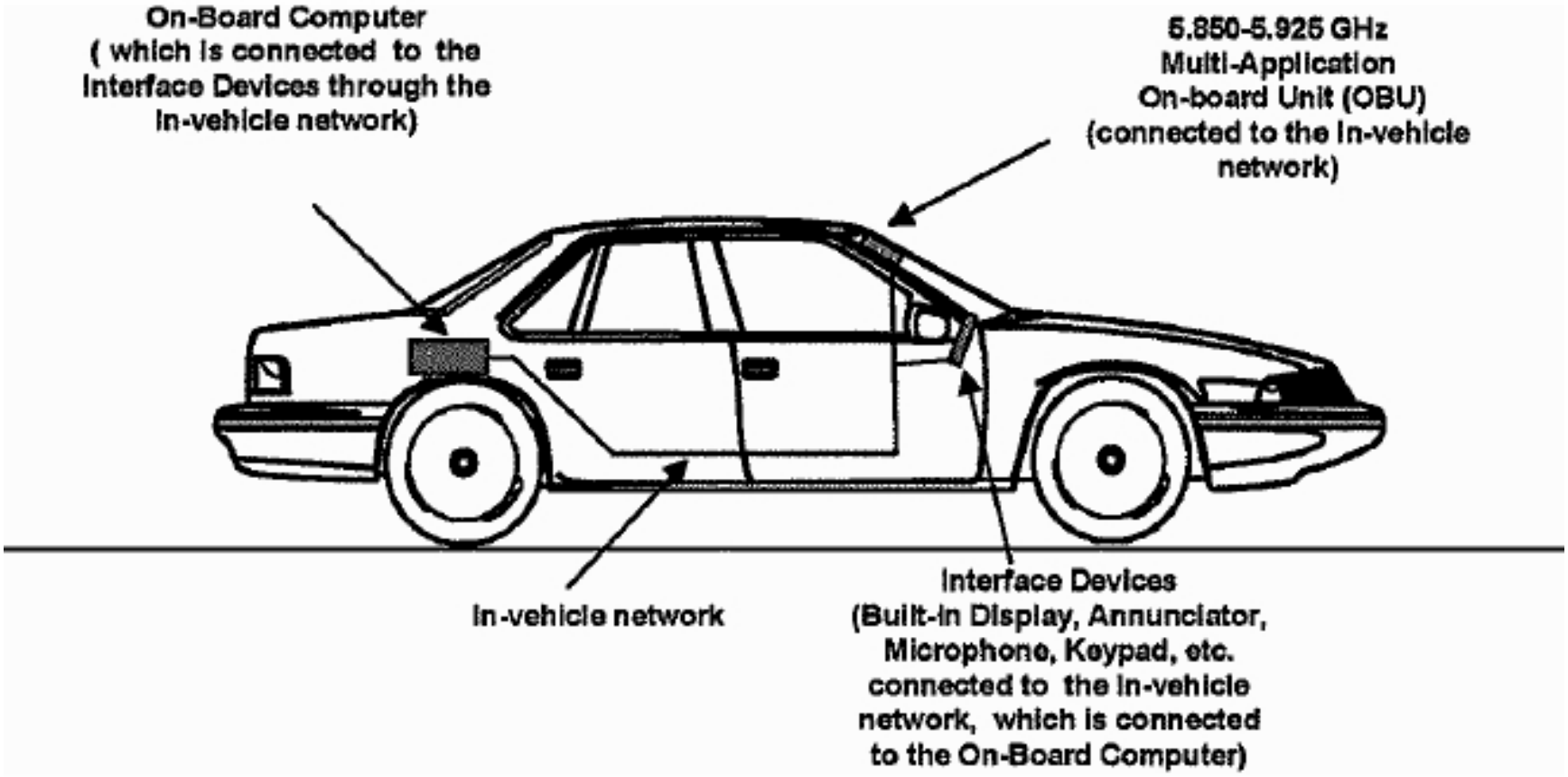
Connection of OBC to ITS App.



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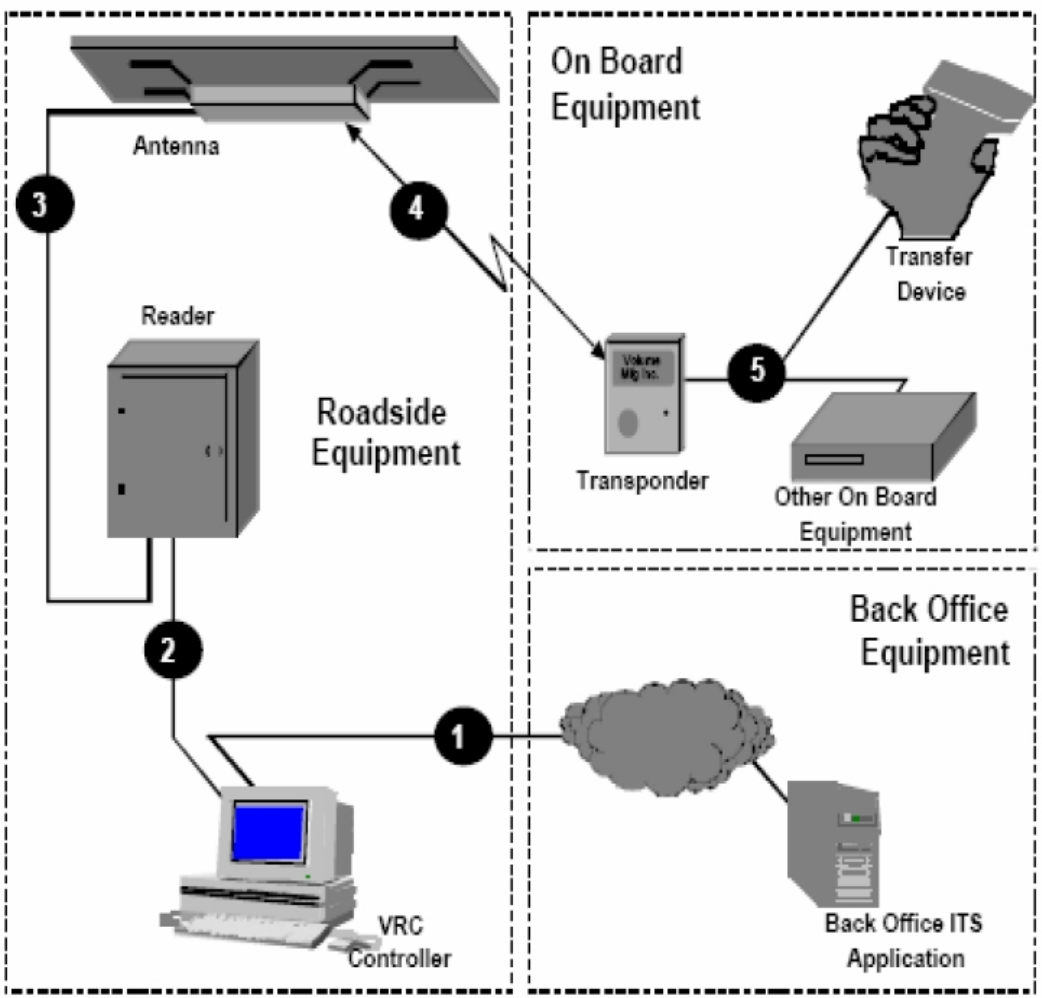
BSS: Basic service set *ITS: Intelligent transportation system* *OBU: Onboard unit* *RSU: Roadside unit*

Connection of OBU to OBC



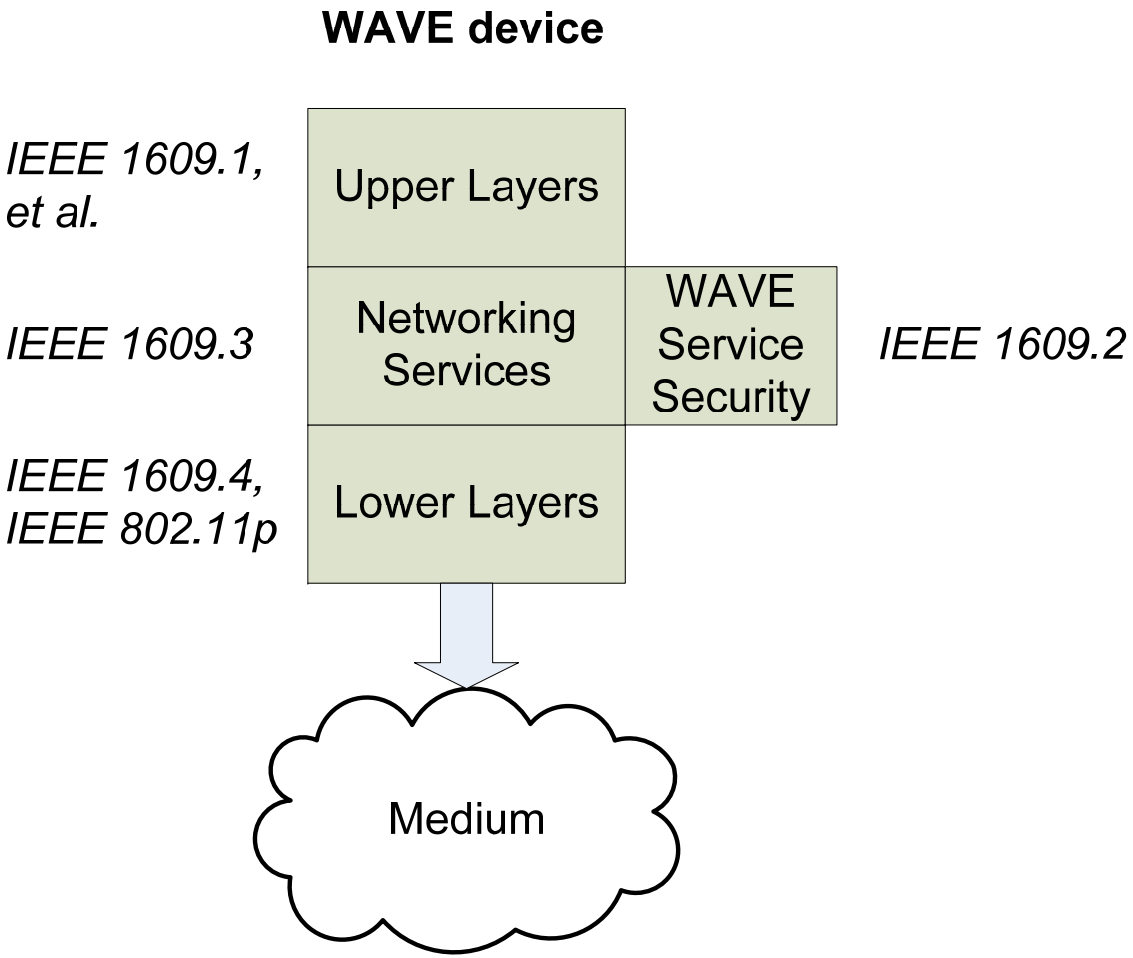
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Connection of OBU to ITS App.



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WAVE Standards

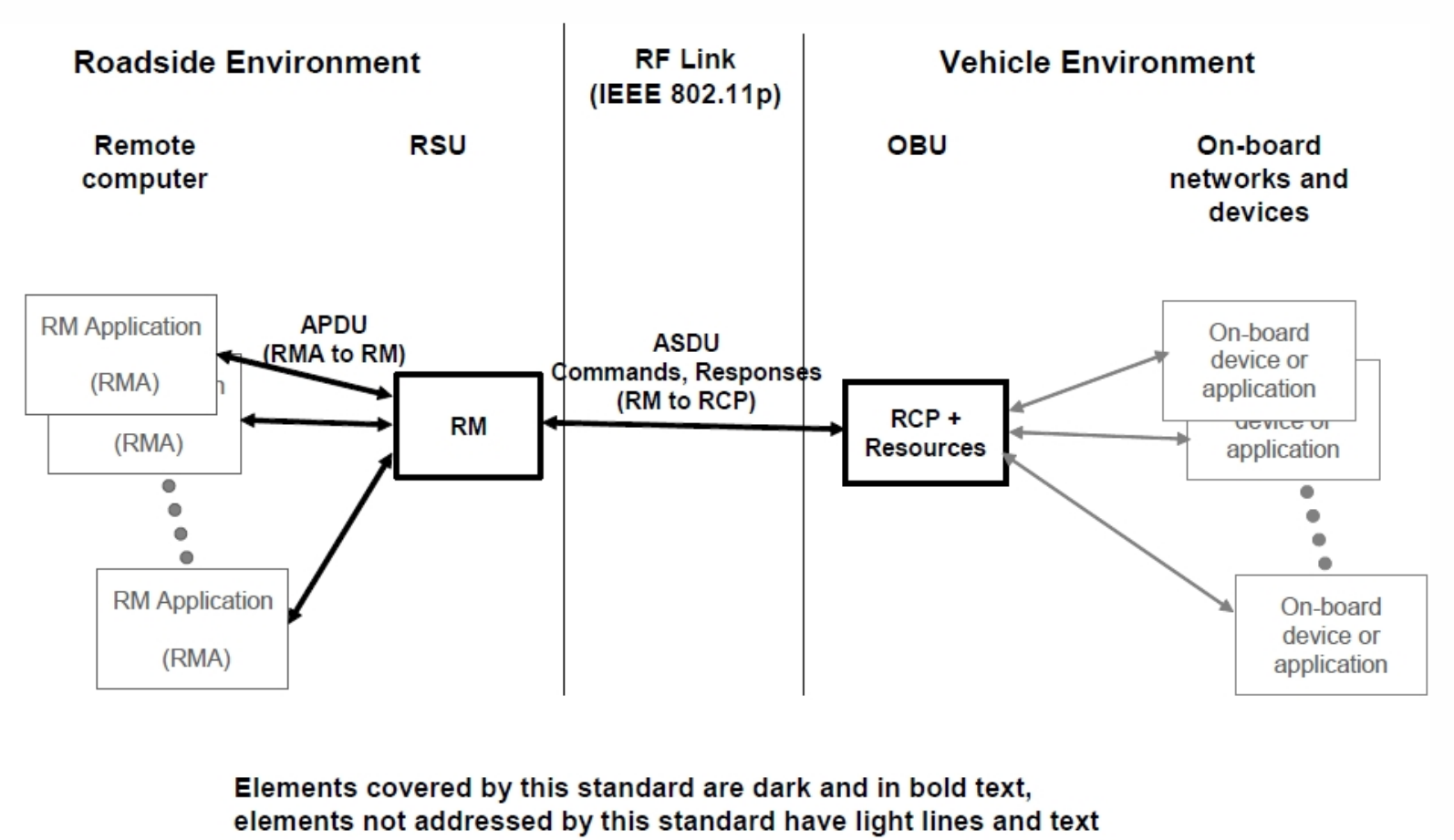


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Purpose of IEEE 1609.1

- OBUs may want to use services provided by applications installed in units far removed from the RSUs.
  - OBUs host an application (Resource Command Processor, or RCP) that uses the service.
  - Third parties (remote from the RSUs) host other applications (Resource Manager Applications, or RMAs) that provide the services.
  - RSUs host an application (Resource Manager, or RM) that acts as middle-man between RCPs and RMAs.
- This standard specifies the RM and the RCP.
- This standard describes how the RM multiplexes requests from multiple RMA, each of which is communicating with multiple OBUs hosting a RCP.
- The purpose of the communication is to provide the RMA access to “resources” such as memory, user interfaces and interfaces to other on-board equipment controlled by the RCP, in a consistent, interoperable and timely manner to meet the requirements of RMA.

Scope of IEEE 1609.1



© 2006 IEEE *OBU: Onboard unit* *RSU: Roadside unit* *RCP: Resource command processor* *RM: Resource manager* *RMA: Resource manager application*

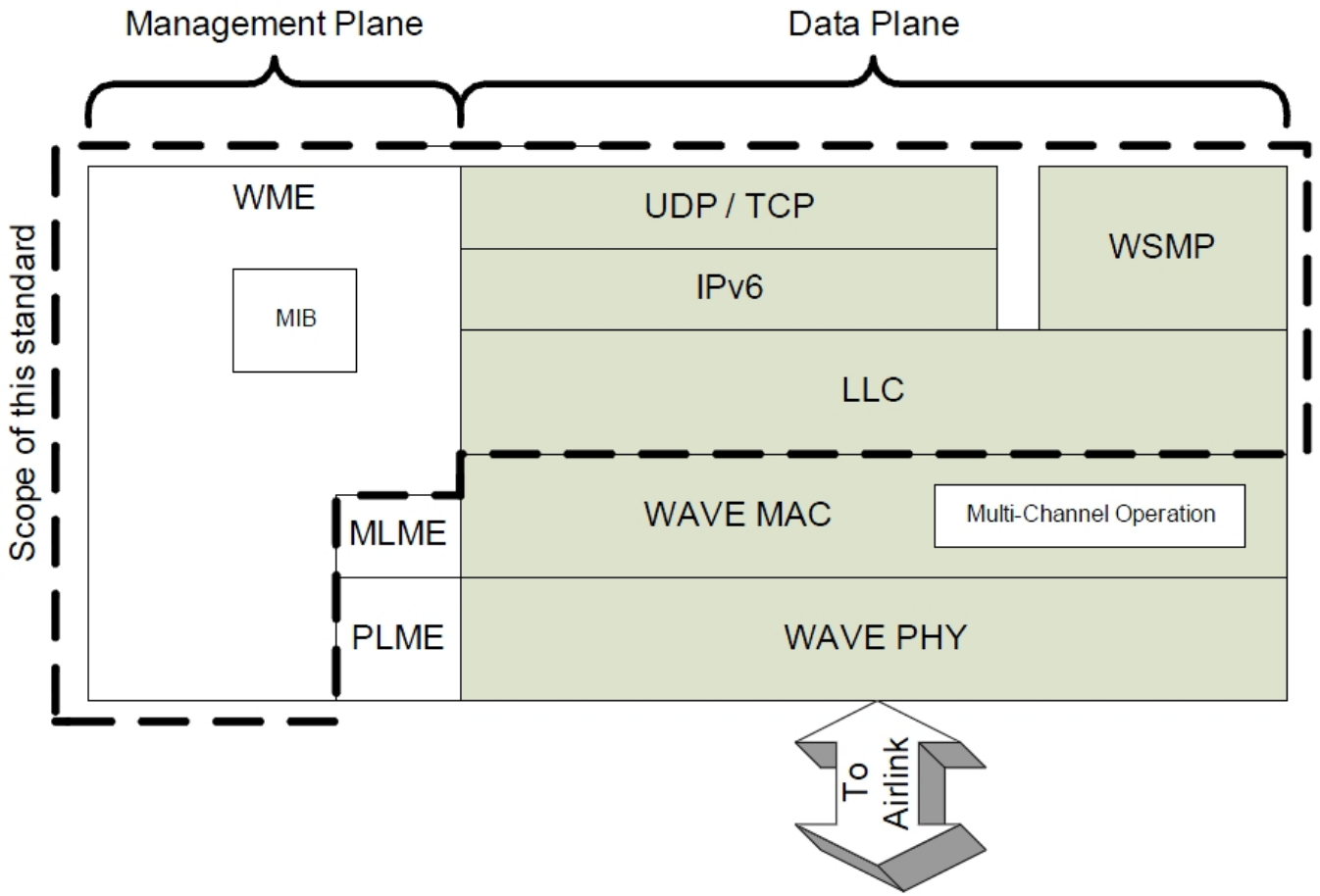
Purpose of IEEE 1609.2

- To define secure formats for management and application messages, and the processing of those secure messages
- To protect from attacks such as
  - Eavesdropping
  - Spoofing
  - Alteration
  - Replay
  - Invasion of privacy
- To guarantee
  - Confidentiality
  - Integrity
  - Authenticity
  - Anonymity

Purpose of IEEE 1609.3

- WAVE networking services
- Layers 3 and 4 of the OSI communications stack
- Addressing and routing services within a WAVE system

Scope of IEEE 1609.3



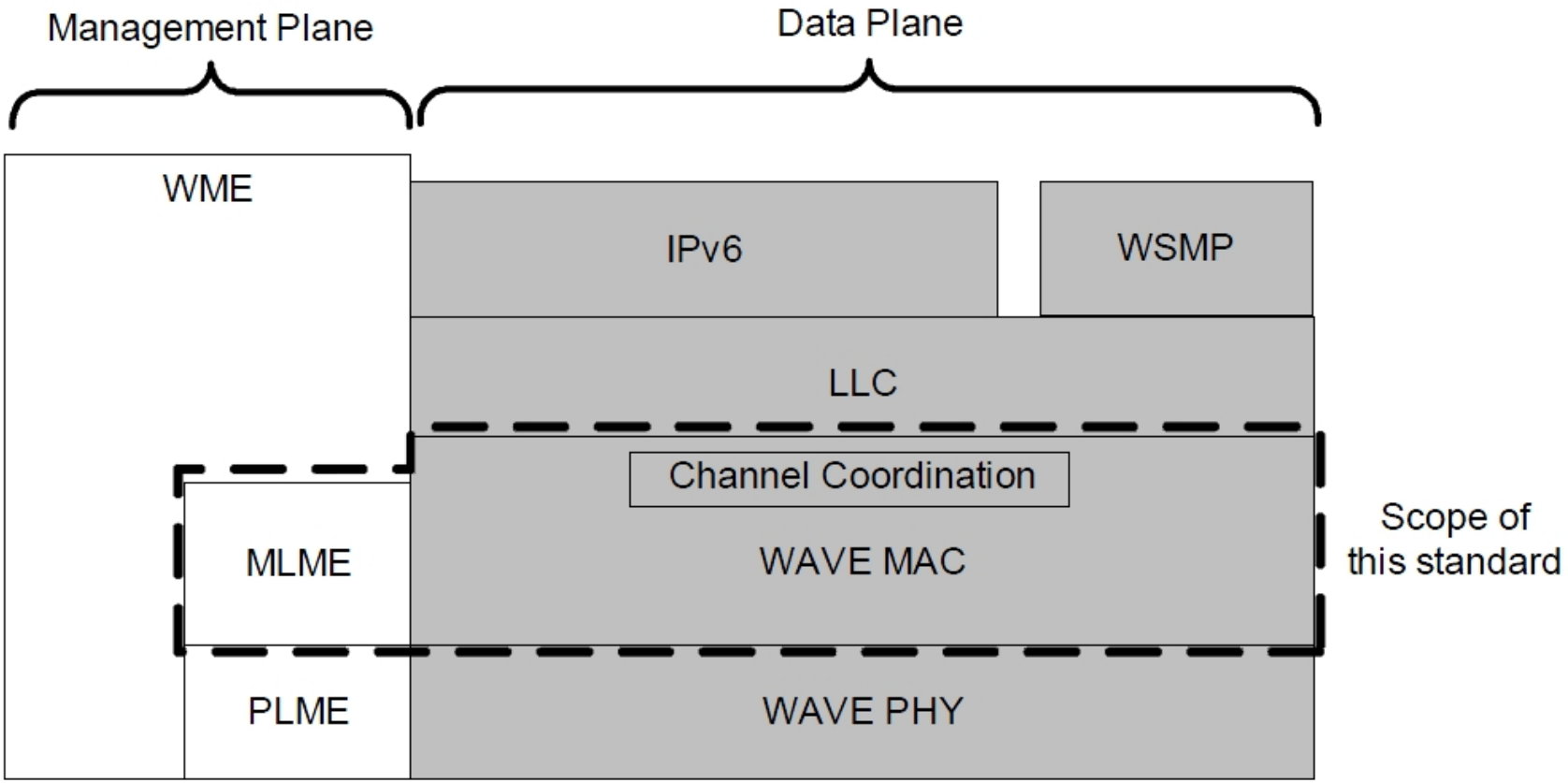
LLC: Logical link control *MIB: Management information base* *MLME: MAC sublayer management entity* *PLME: Physical layer management entity*
WME: WAVE management entity *WSMP: WAVE short message protocol*

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Purpose of IEEE 1609.4

- Multichannel wireless radio operation over WAVE PHY and MAC layers
- Operation of control and service channels
- Operation of interval timers
- Priority access
- Channel switching and routing
- Management services

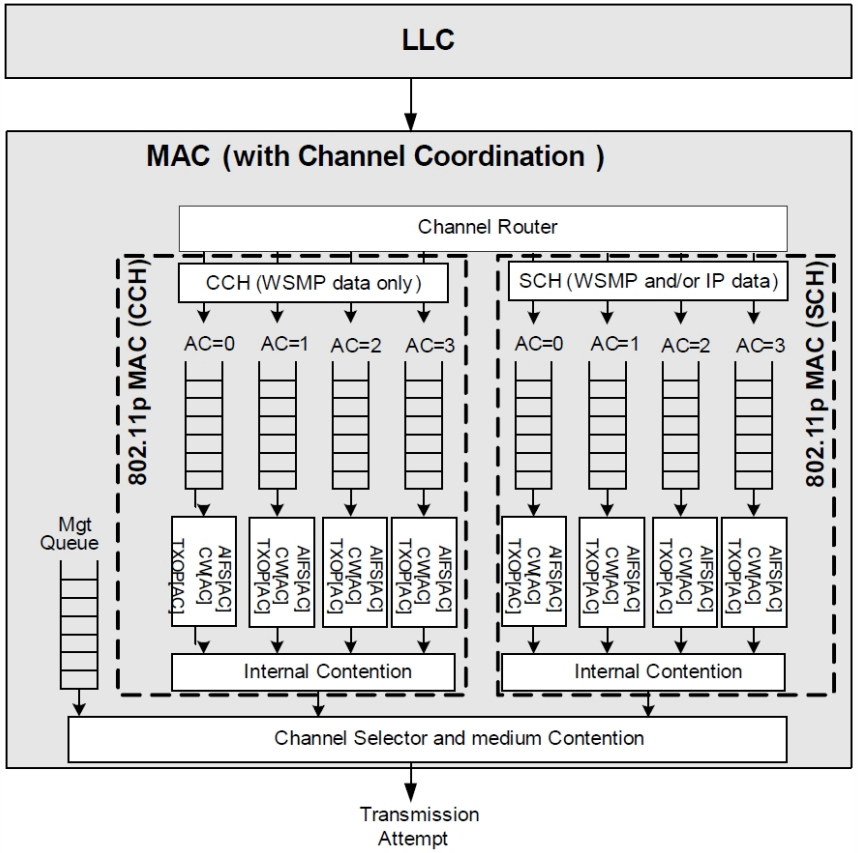
Scope of IEEE 1609.4



LLC: Logical link control *MLME: MAC sublayer management entity* *PLME: Physical layer management entity* *WME: WAVE management entity*
WSMP: WAVE short message protocol

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MAC With Channel Coordination



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AC: Access category *AIFS: Arbitration inter-frame space* *CCH: Control channel* *CW: Contention window* *SCH: Service channel* *TXOP: Transmit opportunity*

Services Provided by IEEE 1609.4

- Channel routing.
  - Routing of data packets from the LLC to the designated channel.
  - WAVE Short Messages (WSMs) are allowed on any type of channel.
  - IP packets are allowed on SCHs only.
- User prioritization.
  - Eight priority levels as defined in IEEE 802.1D.
  - Used to contend for medium access using Enhanced Distributed Channel Access (EDCA) functionality derived from IEEE 802.11e.
- Channel coordination.
  - Guarantees that all devices will be monitoring the CCH at the same time.
  - Guarantees that members of a WBSS will be using their SCH at the same time.
- MSDU transfer
  - On the CCH
  - On the SCHs

AC: Access category AIFS: Arbitration inter-frame space CCH: Control channel CW: Contention window
SCH: Service channel TXOP: Transmit opportunity MSDU: MAC Service Data Unit

IEEE 802.11p

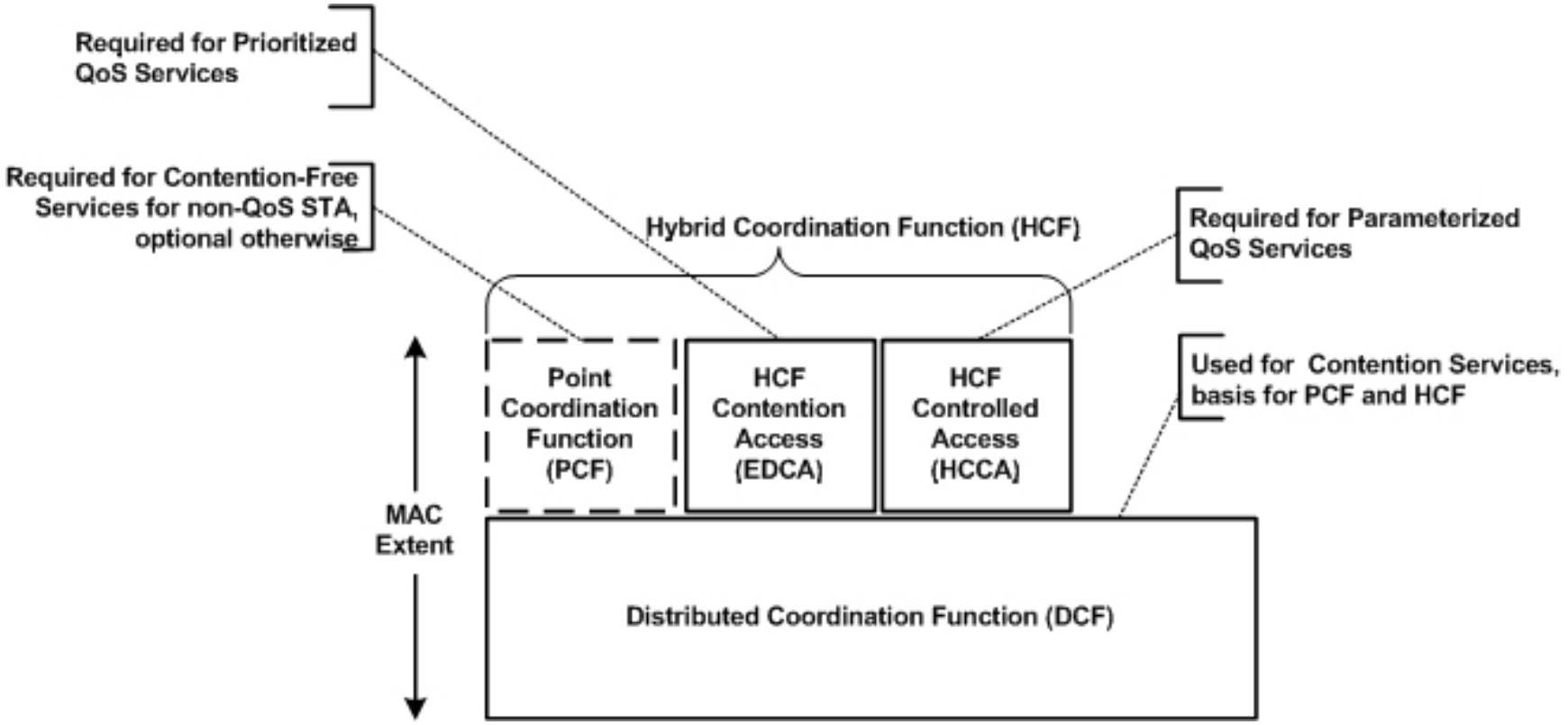
Medium Access Control Layer

Purpose of the MAC Layer

- Channel-access control
  - Mechanisms usually known as multiple access protocols
  - May detect or avoid data-packet collisions (contention based protocols)
  - May establish logical channels (channelization based protocols)
  - Examples:
    - In Ethernet, Carrier Sense Multiple Access/Collision Detection (CSMA/CD)
    - In WLANs, Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA)

- Addressing
  - Unique serial number assigned to each network adapter, known as MAC Address
  - Makes it possible to deliver data packets to a destination within a subnetwork , i.e. a physical network consisting of one or several network segments interconnected by repeaters, hubs, bridges and switches, but not by IP routers

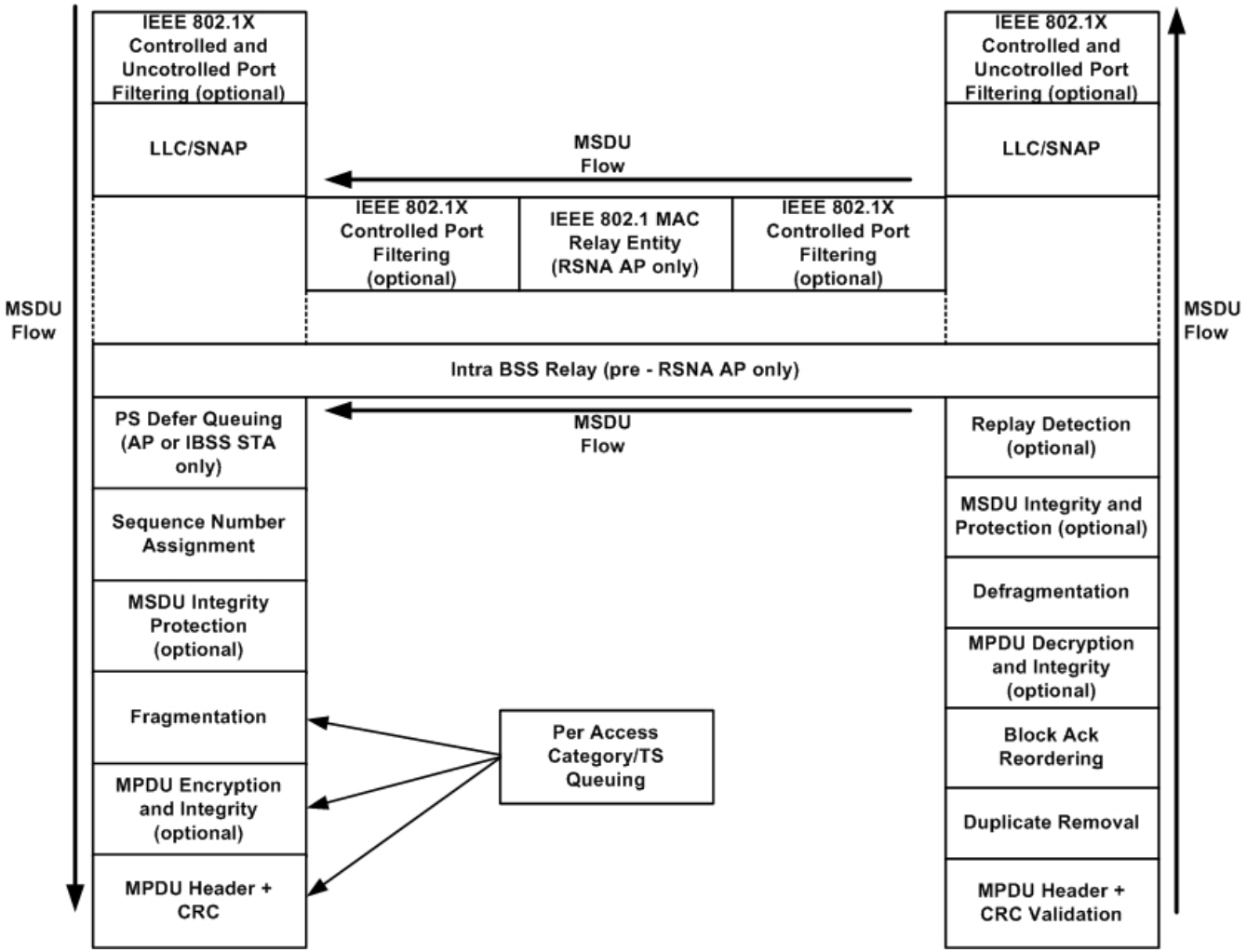
MAC Architecture



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AC: Access category AIFS: Arbitration inter-frame space CCH: Control channel CW: Contention window SCH: Service channel TXOP: Transmit opportunity

MAC Data Plane Architecture



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AP: Access point
BSS: Basic service set
CRC: Cyclic redundancy check
LLC: Logical link control
MSDU: MAC service data unit
SNAP: Subnetwork access protocol
RSNA: Robust security network association
TS: Traffic stream

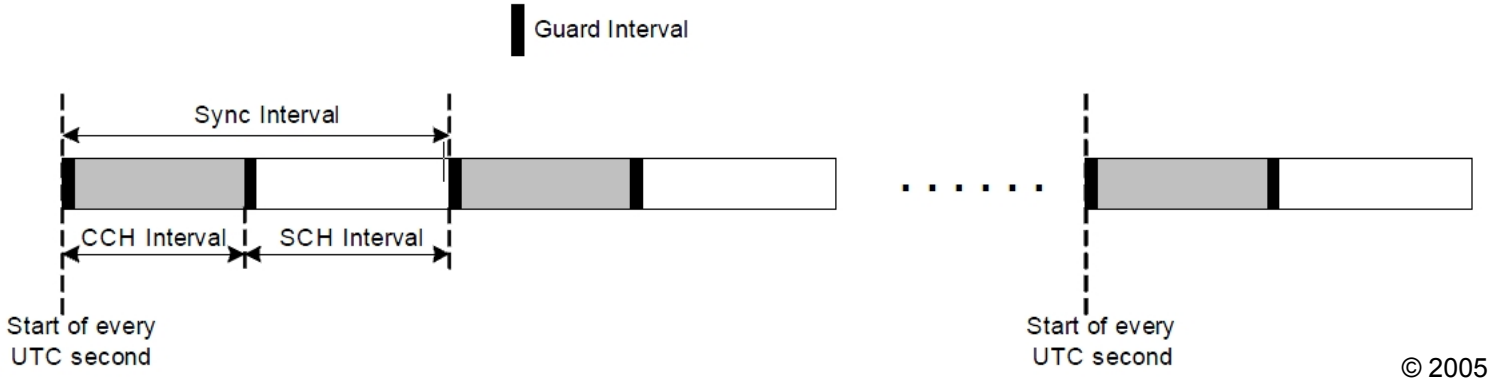
Channel Types

- A single Control Channel (CCH)
  - Reserved for short, high-priority application and system control messages
  - By default, WAVE devices operate here
- Multiple Service Channels (SCHs)
  - For general-purpose application data transfers
  - Visits are arranged via a WBSS (WAVE Basic Service Set)

Channel Coordination

- Synchronized scheme based on Coordinated Universal Time (UTC).
- Assures that all WAVE devices will be monitoring the CCH during a common time interval (CCH Interval).
- Assures that members of a WBSS will be using the corresponding SCH during a common time interval (SCH Interval).
- The sum of the CCH and SCH intervals comprises a Sync Interval.
- At the start of a Sync Interval, all devices must monitor the CCH.
- There are 10 Sync intervals per UTC second.
- Channel intervals are padded with a guard interval.

AC: Access category *AIFS: Arbitration inter-frame space*
CCH: Control channel *CW: Contention window*
SCH: Service channel *TXOP: Transmit opportunity*



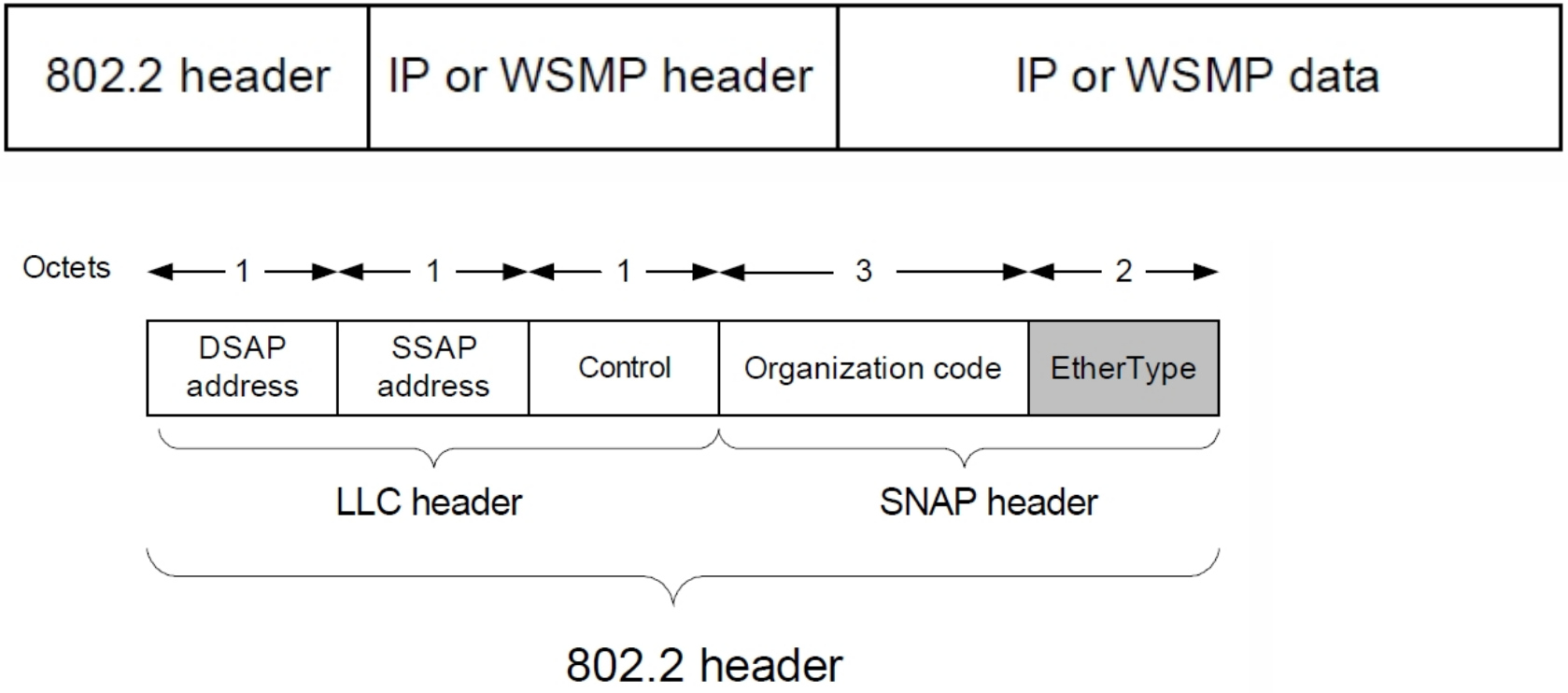
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Communication Protocols

- WAVE accommodates two protocol stacks:
  - Standard Internet Protocol (IPv6).
  - WAVE Short Message Protocol (WSMP).
- WAVE Short Messages (WSMs) may be sent on any channel.
- IP messages may be sent only on SCHs.
- System management frames are sent on the CCH.
- WSMP allows applications to directly control PHY characteristics, such as channel number and transmitter power.

AC: Access category AIFS: Arbitration inter-frame space CCH: Control channel CW: Contention window SCH: Service channel TXOP: Transmit opportunity

Protocol Identification

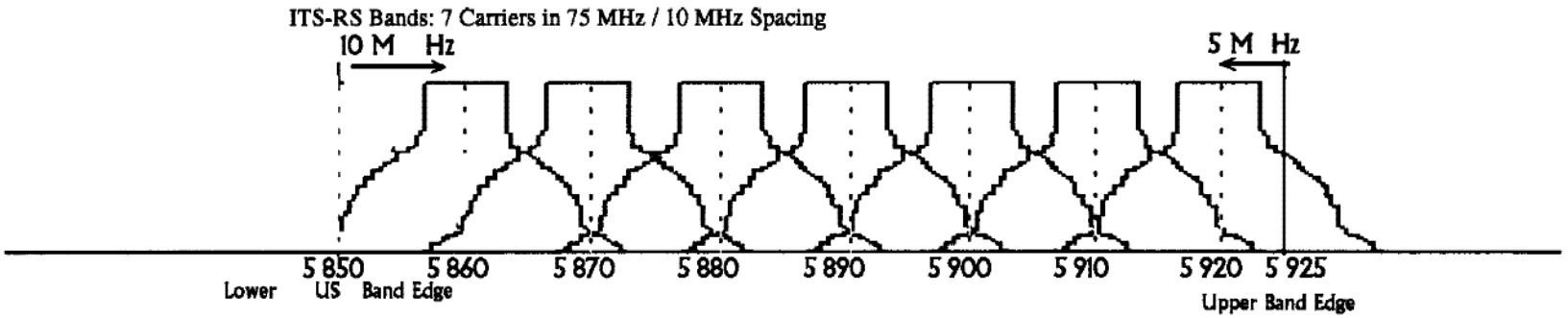


DSAP: Destination service access point *LLC: Logical link control* *SNAP: Subnetwork access protocol*
SSAP: Source service access point *WSMP: WAVE short message protocol*

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Physical Layer

Frequency Plan



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Operating Channels

Channel center frequency (MHz) = 5000 + n_{ch} x 5

Regulatory Domain	Band, GHz	Operating Channel Numbers	Channel Center Frequencies, MHz
United States and Canada	ITS-RS (5.855-5.925)	172	5860
		174	5870
		175	5875
		176	5880
		178	5890
		180	5900
		181	5905
		182	5910
		184	5920

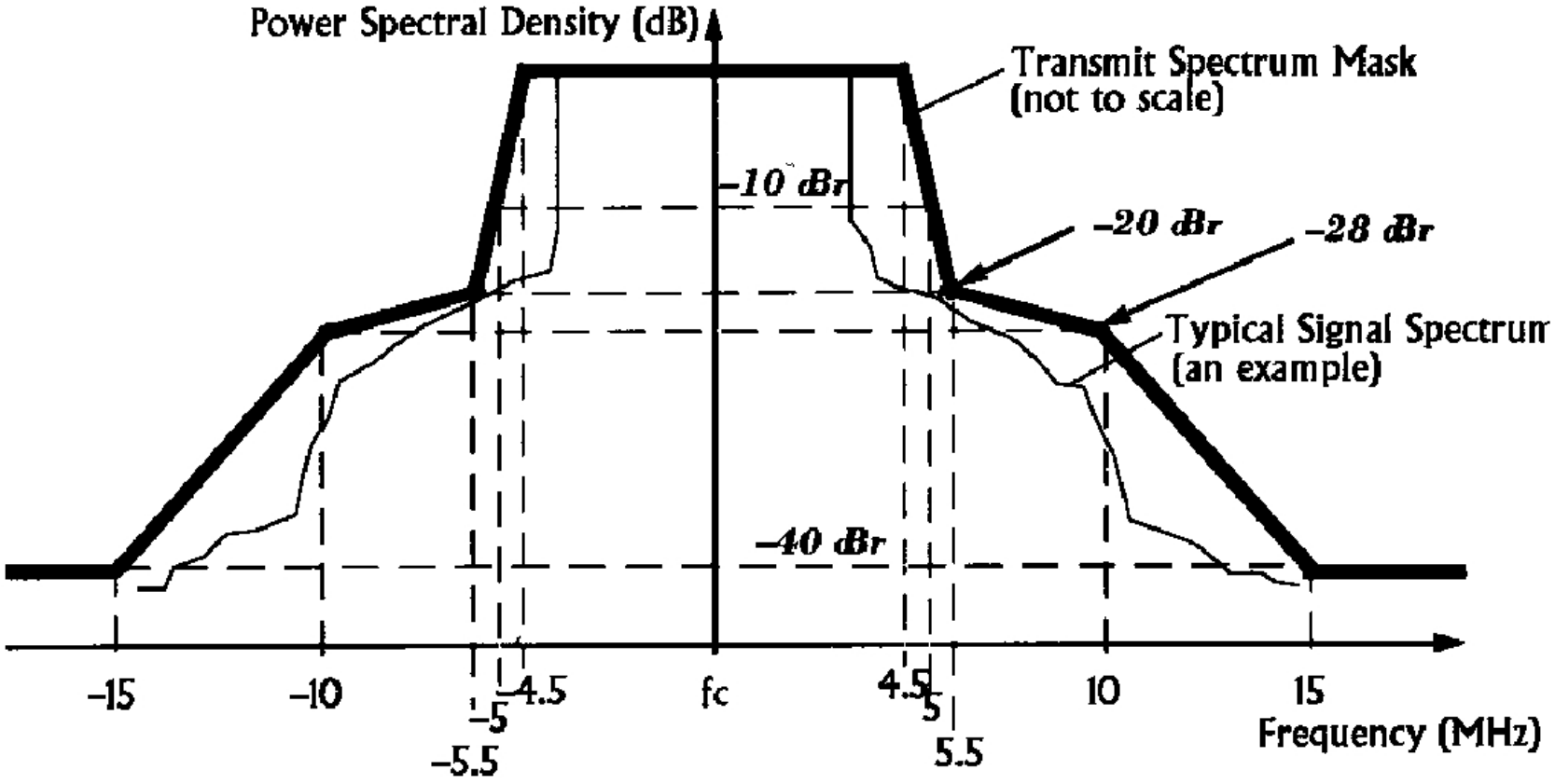
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PHY Specifications

Information Data Rate	3, 4.5, 6, 9, 12, 18, 24, and 27 Mbit/s (3, 6, and 12 Mbit/s are Mandatory)
Modulation	BPSK OFDM QPSK OFDM 16-QAM OFDM 64-QAM OFDM
Error correcting code	K = 7 (64 states) convolutional code
Coding rate	1/2, 2/3, 3/4
Number of subcarriers	52
OFDM symbol duration	8.0 μs
Guard interval	1.6 μs[2](T_{GI})
Occupied bandwidth	8.3 MHz

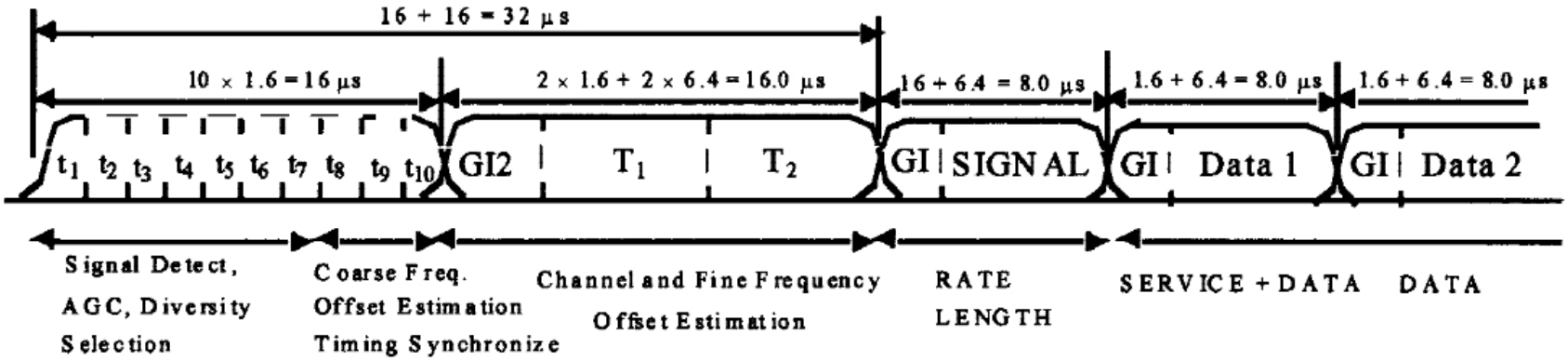
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Class-A Transmit Spectrum Mask



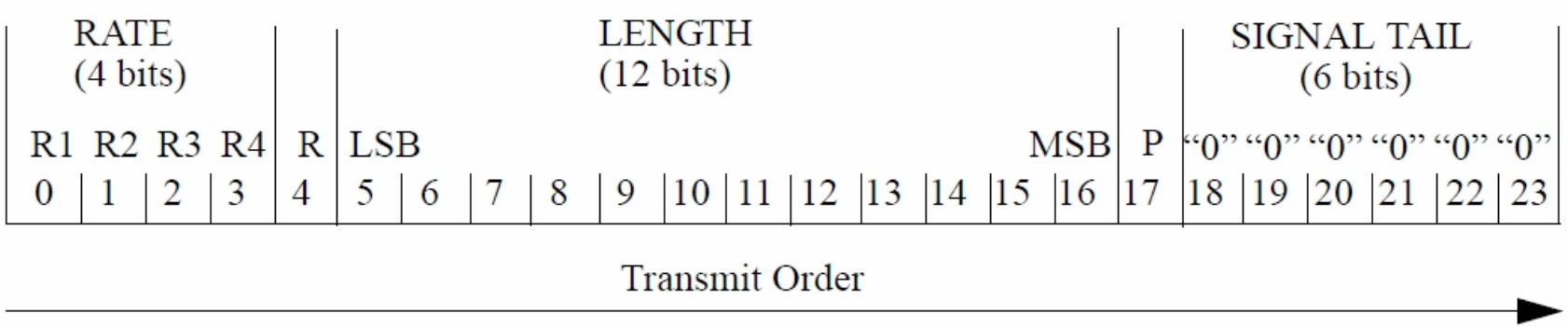
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OFDM Structure



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SIGNAL Symbol



Rate, Mbits/s	R1-R4
3	1101
4.5	1111
6	0101
9	0111
12	1001
18	1011
24	0001
27	0011

BPSK modulation, 3 Mbps, and convolutional coding with rate 1/2.

Rate-Dependent Parameters

Data Rate, Mbits/s	Modulation	Coding Rate, R	Coded Bits per Subcarrier, N_{BPSC}	Coded Bits per OFDM Symbol, N_{CBPS}	Data Bits per OFDM Symbol, N_{DBPS}
3	BPSK	1/2	1	48	24
4.5	BPSK	3/4	1	48	36
6	QPSK	1/2	2	96	48
9	QPSK	3/4	2	96	72
12	16-QAM	1/2	4	192	96
18	16-QAM	3/4	4	192	144
24	64-QAM	2/3	6	288	192
27	64-QAM	3/4	6	288	216

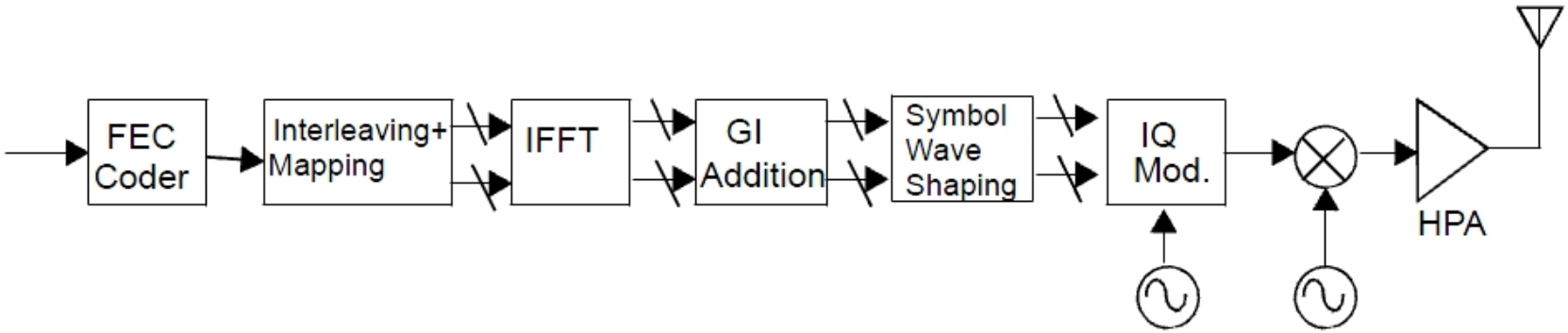
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Timing Parameters

Parameter	Value
N_{SD}: number of data subcarriers	48
N_{SP}: number of pilot subcarriers	4
N_{ST}: number of subcarriers, total	52 (N_{SD}+ N_{SP})
Δ_F: subcarrier frequency spacing	156.25 kHz (=10 MHz/64)
T_{FFT}: IFFT/FFT period	6.4 µs ($1/\Delta_F$)
$T_{PREAMBLE}$: PLCP preamble duration	32 µs (T_{SHORT}+ T_{LONG})
T_{SIGNAL}: duration of the SIGNAL BPSK-OFDM symbol	8 µs (T_{GI}+ T_{FFT})
T_{GI}: GI duration	1.6 µs (T_{FFT}/4)
T_{GI2}: training symbol GI duration	3.2 µs (T_{FFT}/2)
T_{SYM}: symbol interval	8 µs (T_{GI}+ T_{FFT})
T_{SHORT}: short training sequence duration	16 µs (10 × T_{FFT}/4)
T_{LONG}: long training sequence duration	16 µs (T_{GI2}+ 2 × T_{FFT})

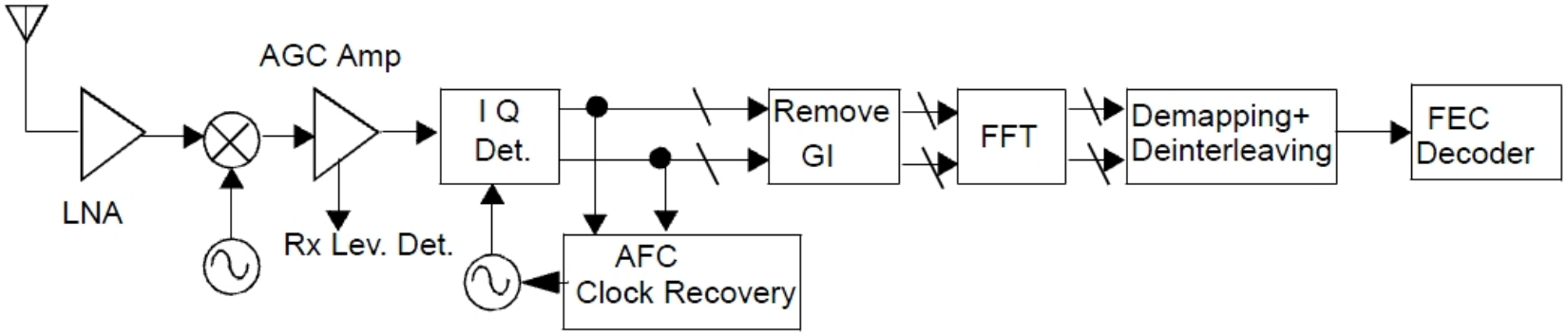
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OFDM Transmitter



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OFDM Receiver



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Other Requirements

- Tx and Rx antenna requirements:
  - Antenna port impedance: 50 Ω (if port is exposed)
  - Right hand circularly polarized

- Operating temperature

Type	Environment	Temperature Range
1	Office	0—40° C
2	Industrial	-20—50° C
3	Industrial	-30—70° C
4	Automotive	-40—85° C

Tx Power Limits for Public Safety

WAVE Channel	Frequency (GHz)	RSU		OBU	
		Max Antenna Input Power (dBm)	Max EIRP (dBm)	Max Antenna Input Power (dBm)	Max EIRP (dBm)
172	5.860	28.8	33.0	28.8	33.0
174	5.870	28.8	33.0	28.8	33.0
175	5.875	10.0	23.0	10.0	23.0
176	5.880	28.8	33.0	28.8	33.0
178	5.890	28.8	44.8	28.8	44.8
180	5.900	10.0	23.0	20.0	23.0
181	5.905	10.0	23.0	20.0	23.0
182	5.910	10.0	23.0	20.0	23.0
184	5.920	28.8	40.0	28.8	40.0

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Tx Power Limits for Private Usage

WAVE Channel	Frequency (GHz)	RSU		OBU	
		Max Antenna Input Power (dBm)	Max EIRP (dBm)	Max Antenna Input Power (dBm)	Max EIRP (dBm)
172	5.860	28.8	33.0	28.8	33.0
174	5.870	28.8	33.0	28.8	33.0
175	5.875	10.0	23.0	10.0	23.0
176	5.880	28.8	33.0	28.8	33.0
178	5.890	28.8	33.0	28.8	33.0
180	5.900	10.0	23.0	20.0	23.0
181	5.905	10.0	23.0	20.0	23.0
182	5.910	10.0	23.0	20.0	23.0
184	5.920	28.8	33.0	28.8	33.0

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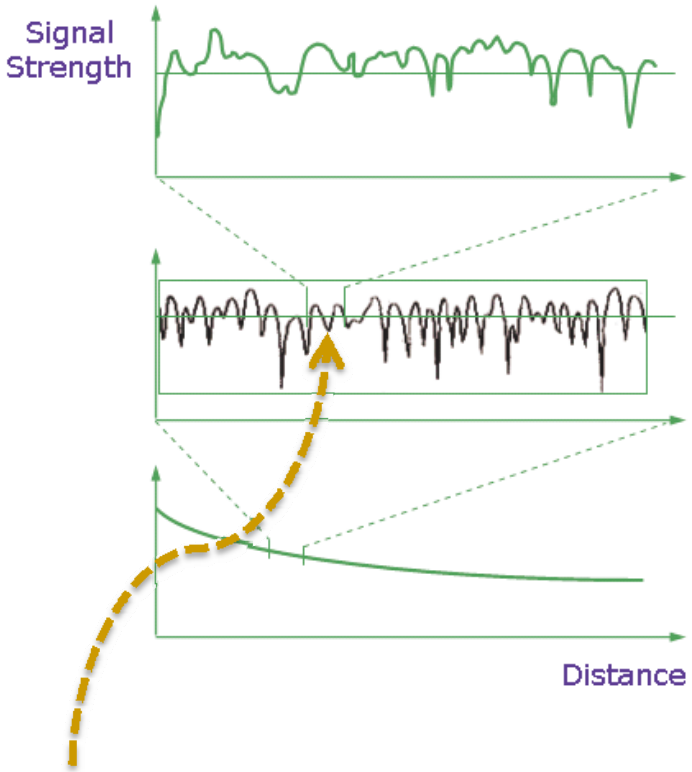
Certification

OmniAir

- Omni: Open Mobile Network Interoperability
- Non-profit trade association
- Established in 2003
- An alliance of DSRC system manufacturers, operators, integrators, application service providers and others
- Mission: To foster and promote the deployment of interoperable 5.9 GHz DSRC systems through the member-defined OmniAir Certification Program

Wireless Channel

Wireless Channel



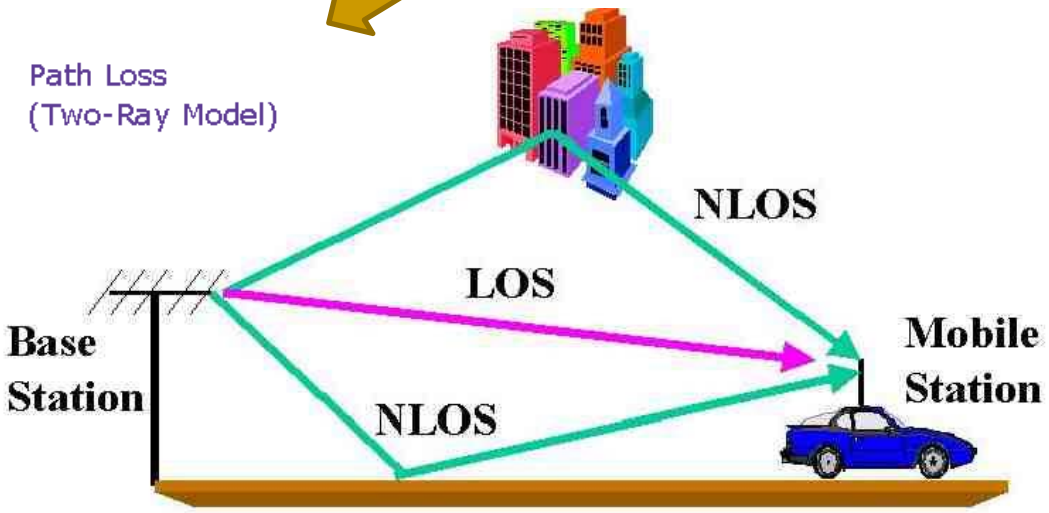
Short-term Fading
(Rayleigh Fading)
(Rician Fading)

VTV main challenge

Long-term Fading
(Lognormal Fading)

Automatic gain control
(AGC) domain

Path Loss
(Two-Ray Model)



WSSUS: any slab selection has same stochastic properties

Small Scale (Short-Term) Fading

- Large scale fading is ignored (AGC might take care of it)
- The received baseband complex signal of a VTV channel is

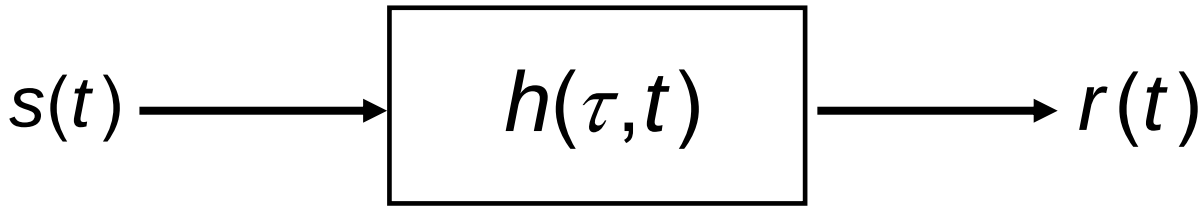
$$r(t) = r_{LOS}(t) + \sum_{n=1}^{L} u\left(t - \tau_n(t)\right)\alpha_n(t)e^{j\left(2\pi f_m \cos\left(\theta\left(t-\tau_n(t)\right)\right)\left(t-\tau_n(t)\right)+2\pi f_c \tau_n(t)\right)}$$

- To provide a useful description or model, we need to somehow define, measure, calculate, or estimate the four parameters:

  L, $\tau_n(t)$, $\alpha_n(t)$, and f_m

Channel Impulse Response

- The VTV channel can be modeled as a time-varying linear system



1. τ dependence causes filtering
2. t dependence causes modulation

- where

$$h(\tau,t)=\sum_{n=0}^{L}\delta\left(t-\tau_n(t)\right)\beta_n(t)$$

Wireless Models

Wireless Design Alternatives

The main objective is to generate $h(\tau, t)$

The alternatives are

- Theoretical models: stochastic (statistical) or geometric (ray tracing)
- Hardware channel emulation
- Software simulation
- Recorded channels

Basic Theoretical Model

- The multipath fading for a channel manifests itself in two effects
  1. Time spreading (in τ) of the symbol duration within the signal, which is equivalent to filtering and bandlimiting
  2. A time-variant behavior (in *t*) of the channel due to motion of the receiver, transmitter, changing environment, or movement of reflectors and scatters
- The random fluctuations in the received signal due to fading can be modeled by treating the channel impulse response $h(\tau,t)$ as a random process in *t*
- If at any time *t,* the probability density functions of the real and imaginary parts are Gaussian. This model implies that for each the ray is composed of a large number or irresolvable components
  - For zero mean, the envelope has Rayleigh pdf
  - For nonzero mean, the envelope has Ricean pdf

Scattering Function: delay-power

- For a wide sense stationary uncorrelated scattering (WSSUS) channel assumption, the autocorrelation is a function of delay and difference in time

$$R_h(\tau, \Delta t) \equiv E\left[h^*(\tau, t)h(\tau, t+\Delta t)\right]$$

- From the engineer's point of view, the **scattering function** is perhaps the most important statistical measure of the random multipath channel

$$S(\tau, \nu) = \int_{-\infty}^{\infty} R_h(\tau, \Delta t)e^{-j2\pi\nu\Delta t}d\Delta t$$

- The **delay-power profile** is defined as

$$p(\tau) = \int_{-\infty}^{\infty} S(\tau, \nu)d\nu$$

Scattering Function: Doppler

- The Doppler power spectrum is

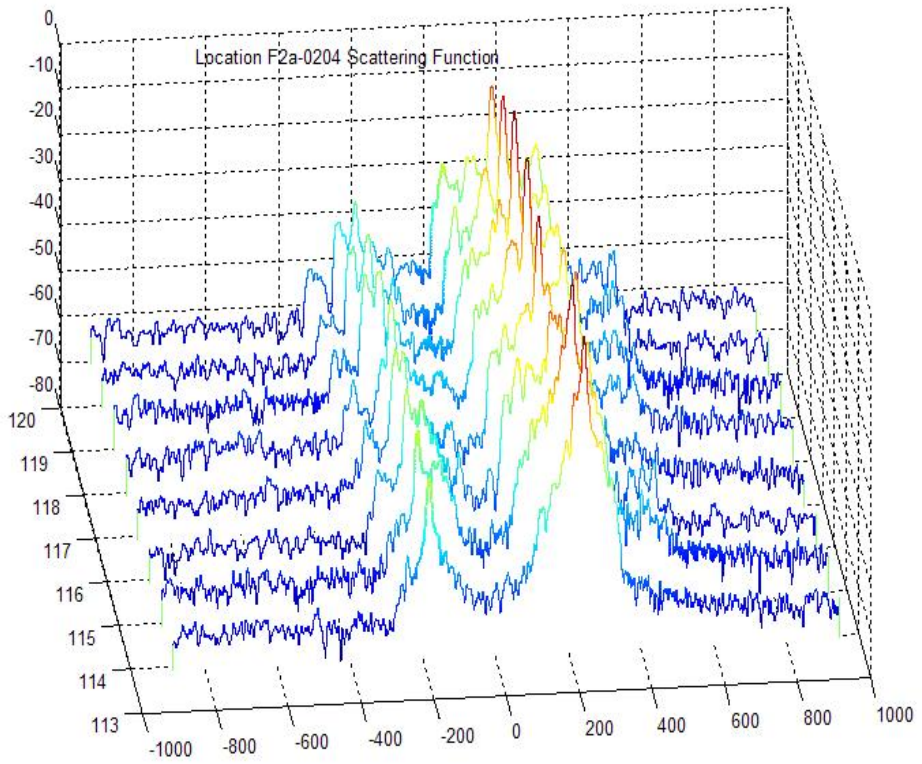
$$S(\nu) = \int_{-\infty}^{\infty} S(\tau, \nu) d\tau$$

- For example, the Jakes dense scatters model, the Doppler power spectrum is

$$S(\nu) = \frac{1}{\pi f_m \sqrt{1 - \left(\frac{\nu}{f_m}\right)^2}}, \quad |\nu| \leq f_m$$

Scattering Function Example

- Example from 0.7 seconds of data
- Doppler as a function of tap



VTV Statistical Model

- The time correlation function for a Rayleigh distributed complex envelope assuming uniform scattering and two vehicles in motion is

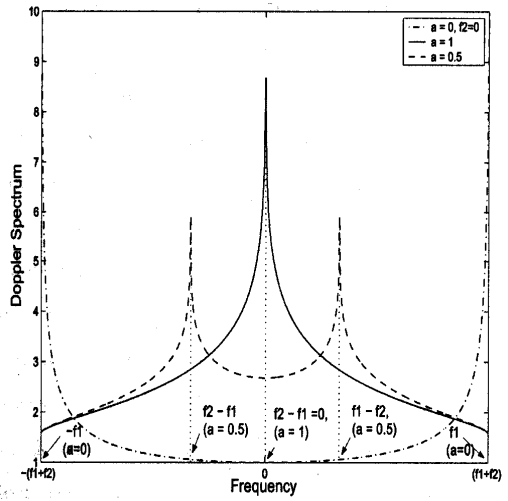
$$R_v(\Delta t) = \sigma_1^2 J_0(2\pi f_{m1}\Delta t) J_0(2\pi f_{m2}\Delta t)$$

- The Doppler spectra assuming uniform 2-D scattering and omni-directional transmit and receive antennas

$$S(\nu) = \frac{\sigma_1^2}{\pi^2 f_{m1}\sqrt{a}} K\left(\frac{1+a}{2\sqrt{a}}\sqrt{1-\left(\frac{\nu}{(1+a)f_{m1}}\right)^2}\right)$$

where

$$f_{m2} = a f_{m1}$$



A. S. Akki and F. Haber, "A statistical model of mobile-to-mobile land communication channel," in *IEEE Transactions on Vehicular Technology*, pp. 2–7, February 1986

Another Statistical Model: double-ring

- A “double-ring” model defines an individual ring of uniformly spaced scatterers for both the BS and the MS, which causes each transmitted path to undergo two reflections, one for each ring
- The autocorrelation for this model is

$$R_h(\tau) = J_0(2\pi f_1 \tau) J_0(2\pi f_2 \tau)$$

C. S. Patel, G. L. Stüber, and T. G. Pratt, “Simulation of Rayleigh faded mobile-to-mobile communication channels,” in *Proceedings of the IEEE Vehicular Technology Conference*, vol.1, pp. 163-167, October 2003

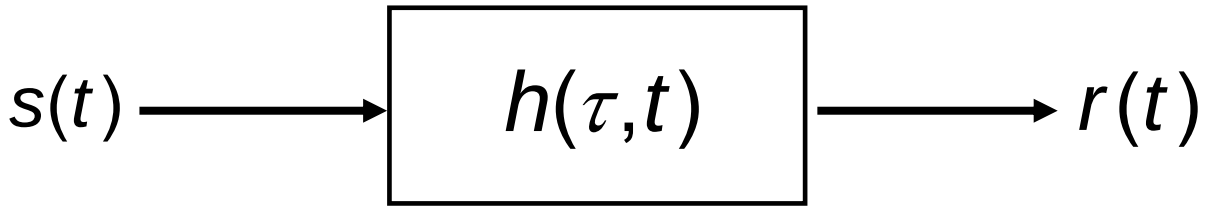
What to Do with or How to Use the Theoretical Models?

- We need to remember that the models derivations assume stochastic processes such as uniform distribution of scatters or normal probability densities in their amplitude variations
- There are plenty of random sources available that we can use to generate signals that behave as the theoretical models
- Once we have this signals, we use them to amplitude modulate the transmitted signal, i.e., we generate the

$$\beta_n(t)$$

Channel Impulse Response (Repeat)

- The VTV channel can be modeled as a time-varying linear system

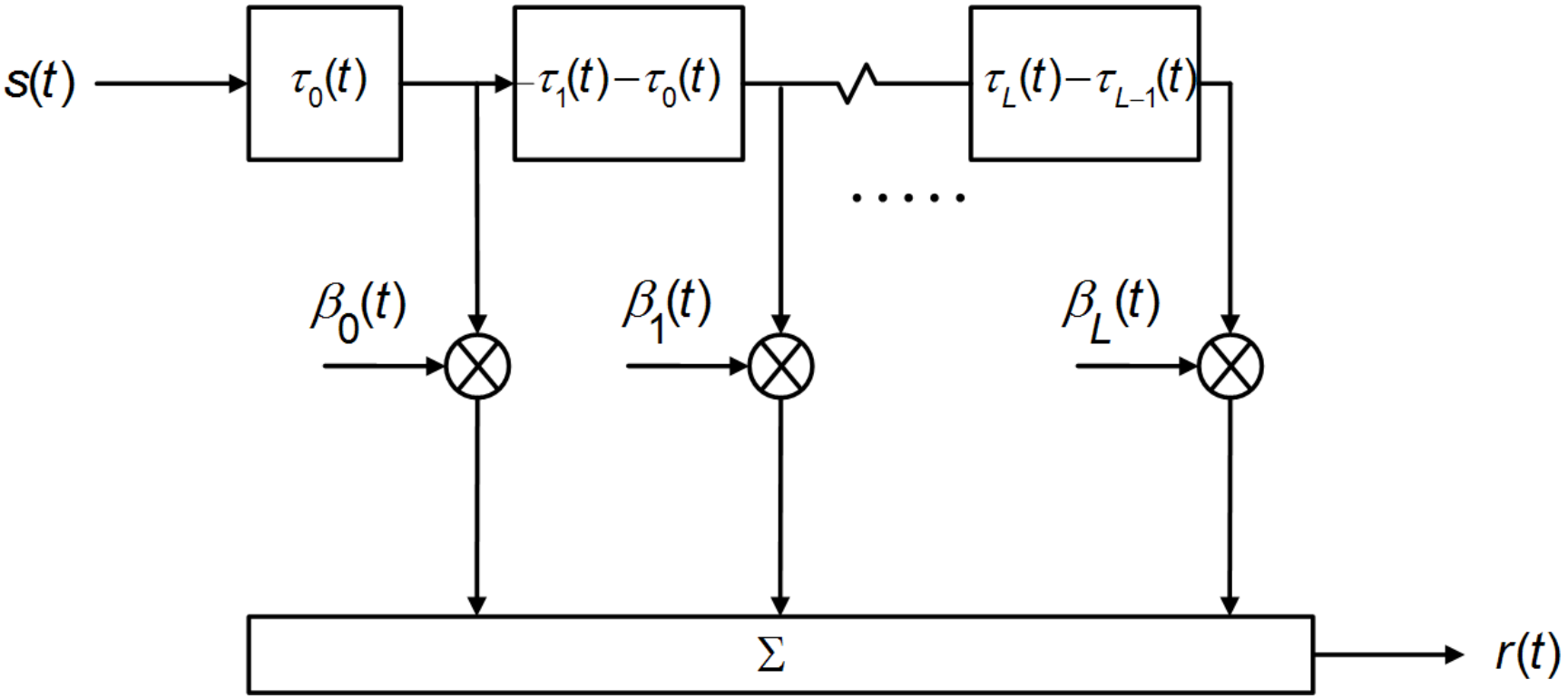


1. τ dependence causes filtering
2. t dependence causes modulation

- where

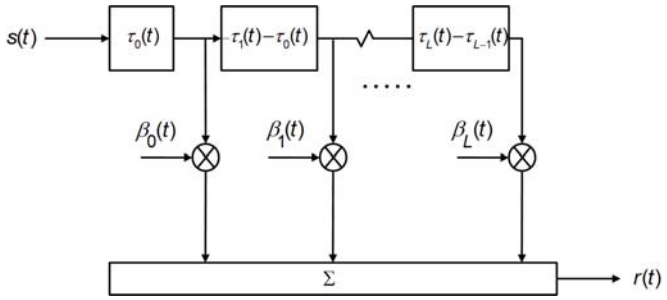
$$h(\tau,t)=\sum_{n=0}^{L}\delta\left(t-\tau_n(t)\right)\beta_n(t)$$

Conventional Tapped-Delay Line Model to Implement $h(\tau,t)$



Characterization of $\beta_n(t)$

- Assume WSSUS model:
  - Independent $\beta_n(t)$
  - Stationary random process
- Additional assumptions:
  - Complex Gaussian
  - Can be nonzero mean
- We characterize $\beta_n(t)$ by its
  - K-factor
  - Power spectral density (PSD)



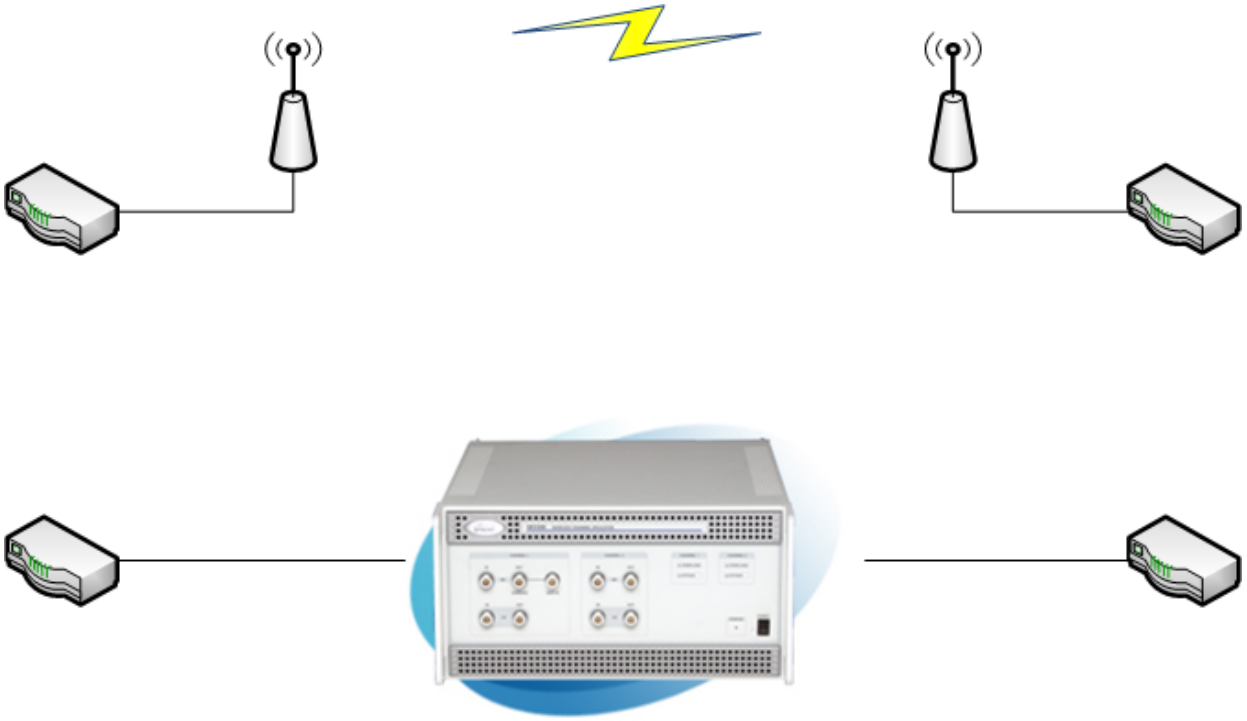
Wireless Design Alternatives

Is There an Easier Way?

- Instead of developing the modulation vectors, we can use available systems

- Hardware: Channel Emulators, e.g. Spirent SR 5500
- Software: Channel Simulators, e.g. Mathworks Simulink Communications Blockset

Channel Emulator



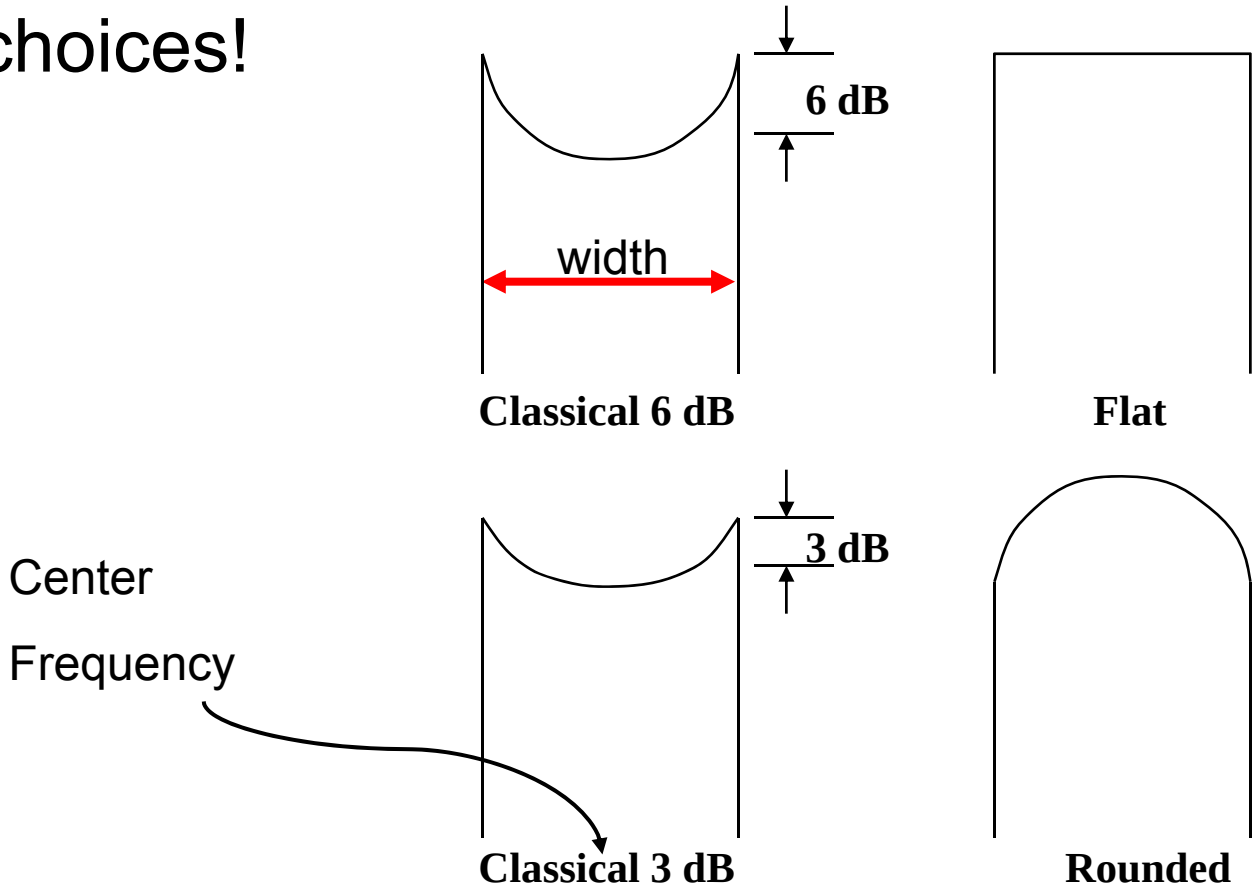
- A channel emulator is a device or machine that “replaces” a real channel for laboratory testing
- Certification tests are performed using channel emulators

Required Channel Emulator Parameters

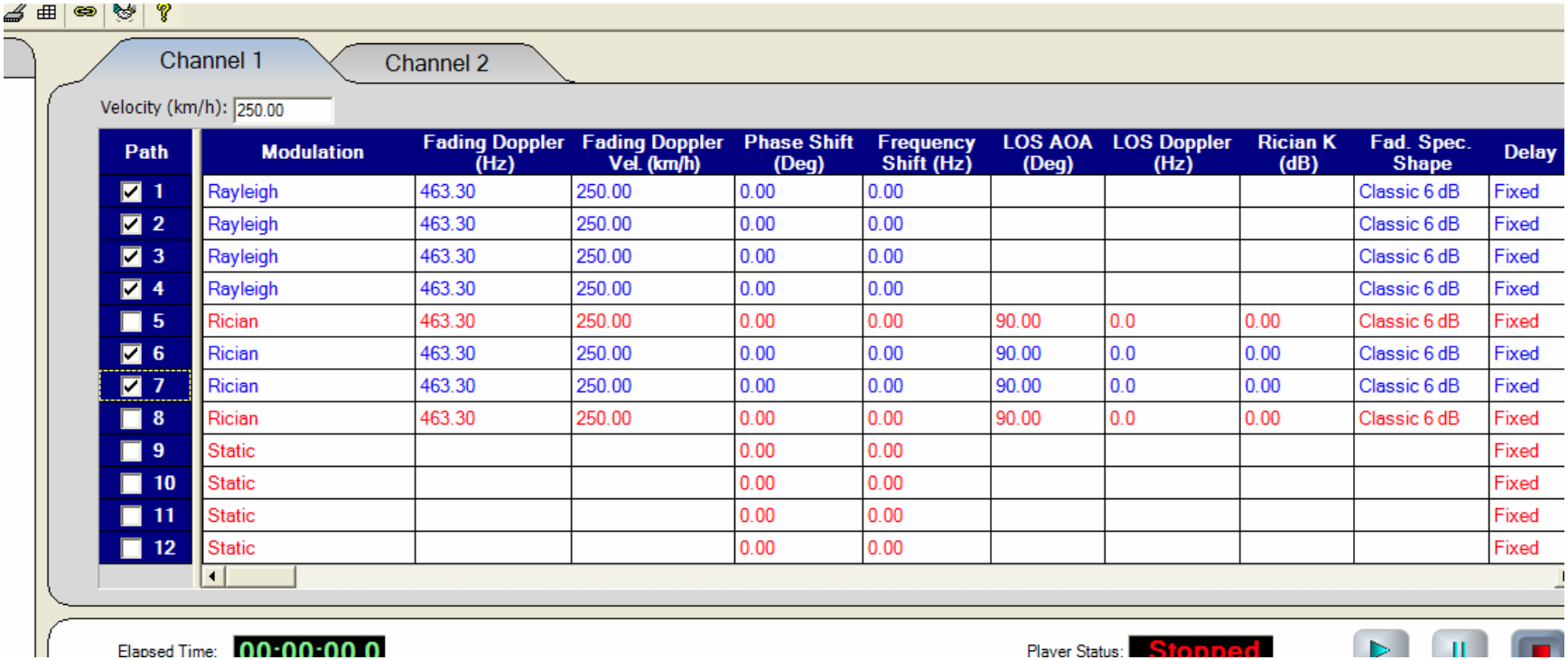
- Number of paths
- For each path:
  - Relative time delay
  - Relative path loss
  - K-factor
    - Amplitude
    - Spectral line location
  - Doppler spectrum
    - Shape
    - Width
    - Center frequency

Channel Emulator Doppler Spectrum Shapes

- Only four choices!



Channel Emulator Parameter Input



Channel 1 | Channel 2

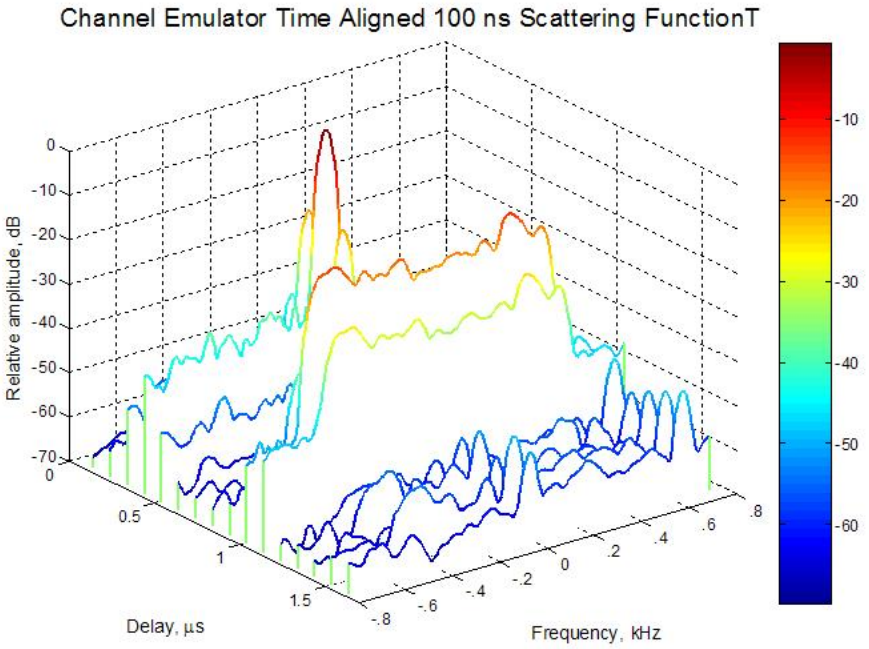
Velocity (km/h): 250.00

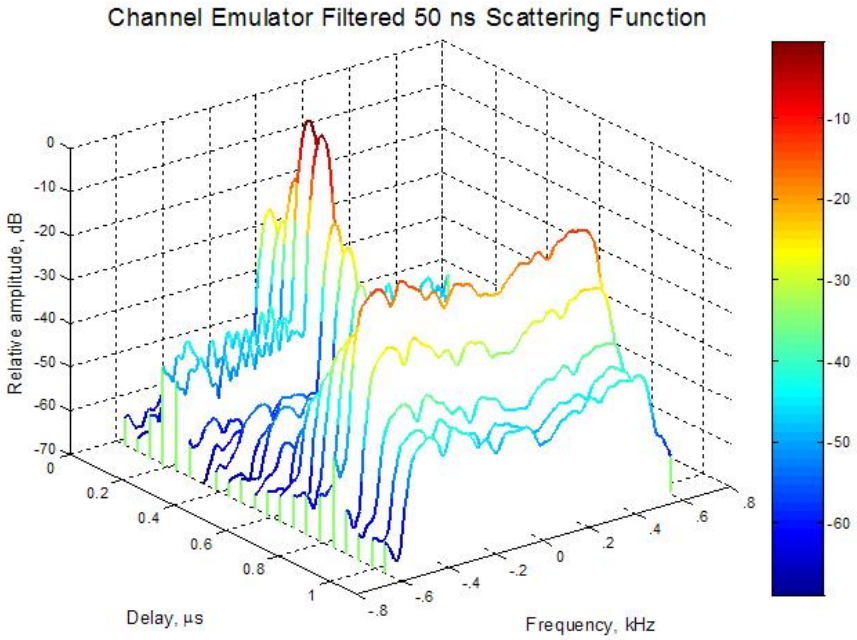
Path	Modulation	Fading Doppler (Hz)	Fading Doppler Vel. (km/h)	Phase Shift (Deg)	Frequency Shift (Hz)	LOS AOA (Deg)	LOS Doppler (Hz)	Rician K (dB)	Fad. Spec. Shape	Delay
☑ 1	Rayleigh	463.30	250.00	0.00	0.00				Classic 6 dB	Fixed
☑ 2	Rayleigh	463.30	250.00	0.00	0.00				Classic 6 dB	Fixed
☑ 3	Rayleigh	463.30	250.00	0.00	0.00				Classic 6 dB	Fixed
☑ 4	Rayleigh	463.30	250.00	0.00	0.00				Classic 6 dB	Fixed
☐ 5	Rician	463.30	250.00	0.00	0.00	90.00	0.0	0.00	Classic 6 dB	Fixed
☑ 6	Rician	463.30	250.00	0.00	0.00	90.00	0.0	0.00	Classic 6 dB	Fixed
☑ 7	Rician	463.30	250.00	0.00	0.00	90.00	0.0	0.00	Classic 6 dB	Fixed
☐ 8	Rician	463.30	250.00	0.00	0.00	90.00	0.0	0.00	Classic 6 dB	Fixed
☐ 9	Static			0.00	0.00					Fixed
☐ 10	Static			0.00	0.00					Fixed
☐ 11	Static			0.00	0.00					Fixed
☐ 12	Static			0.00	0.00					Fixed

Elapsed Time: 00:00:00.0

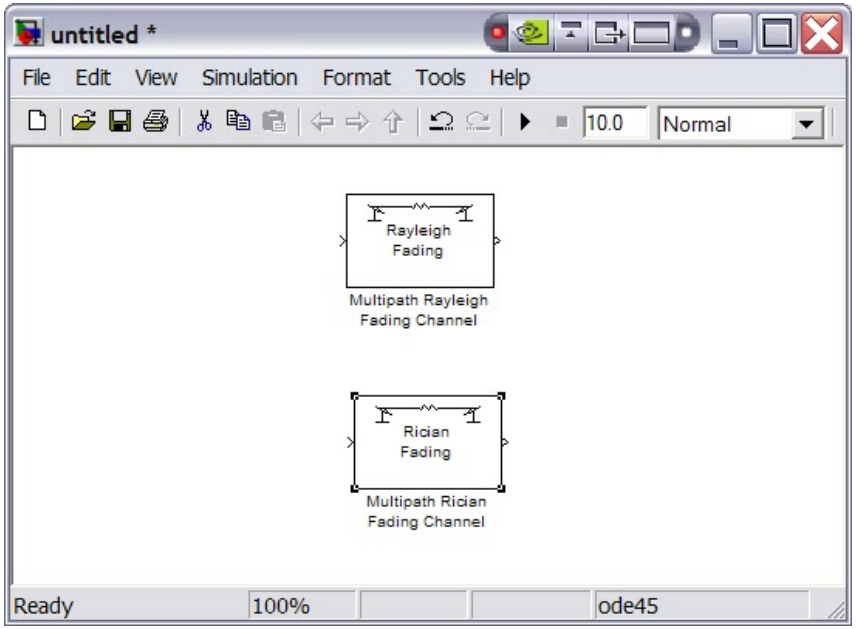
Player Status: Stopped

Examples of Scattering Functions Produced by a Channel Emulator





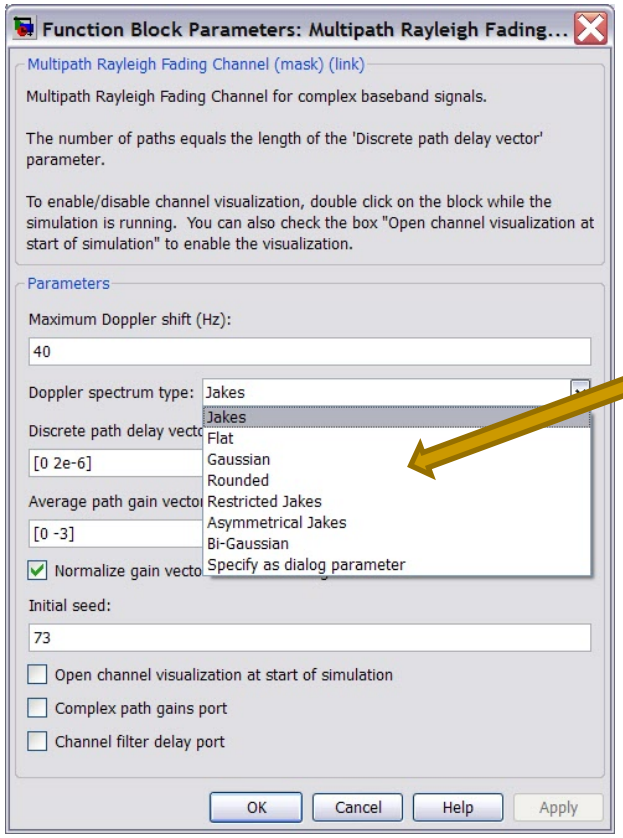
Channel Simulation



- Simulink Multipath Rayleigh and Rician Fading Channels Blocksets
  - One blockset for each path
  - Similar Doppler Spectrum Options

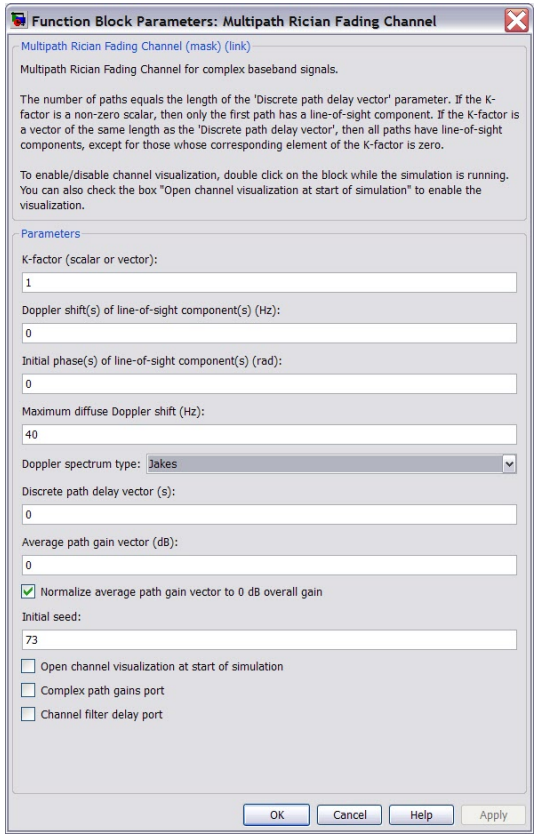
Channel Simulation Parameters

Rayleigh Fading Input Parameters



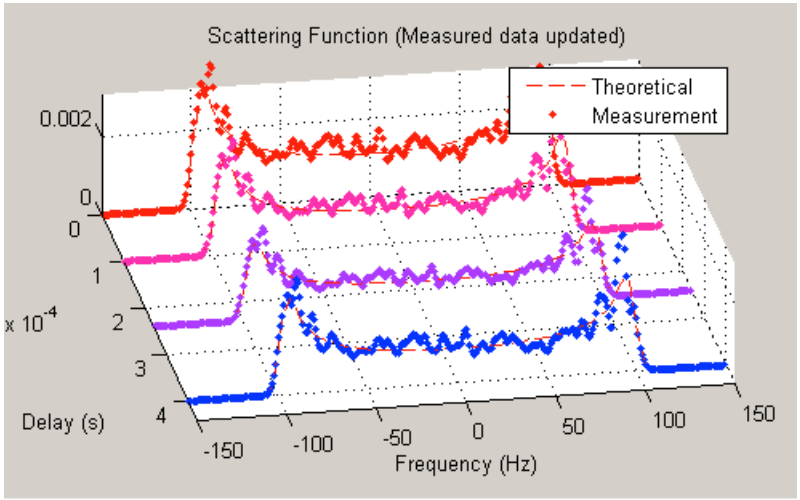
8 Doppler Spectra

Rician Fading Input Parameters

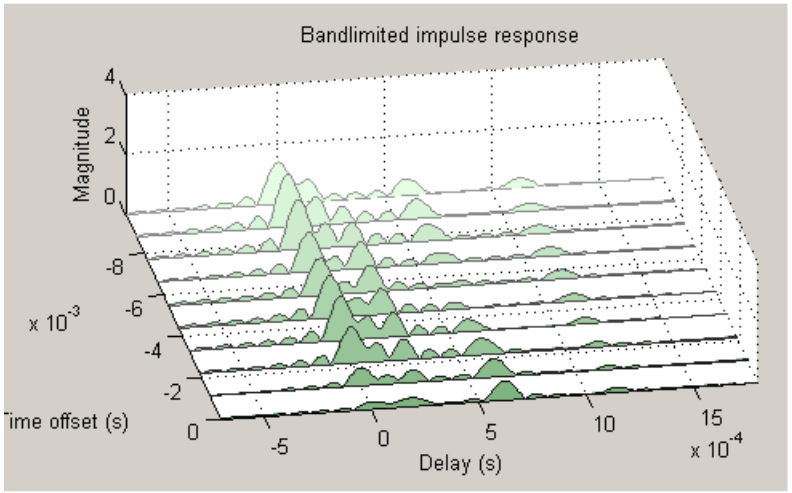


Examples of Simulated Channels

Scattering Function



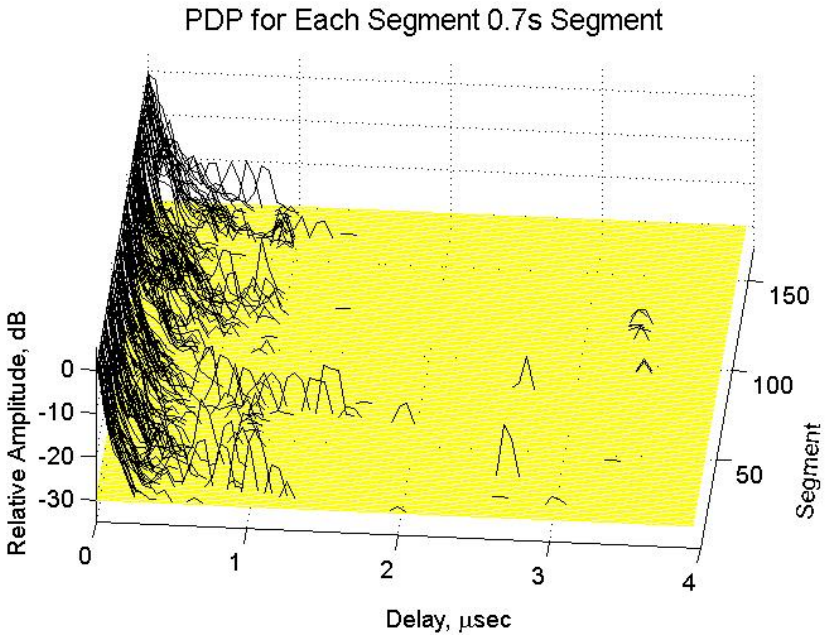
Impulse Responses



Wireless Channel Sounding

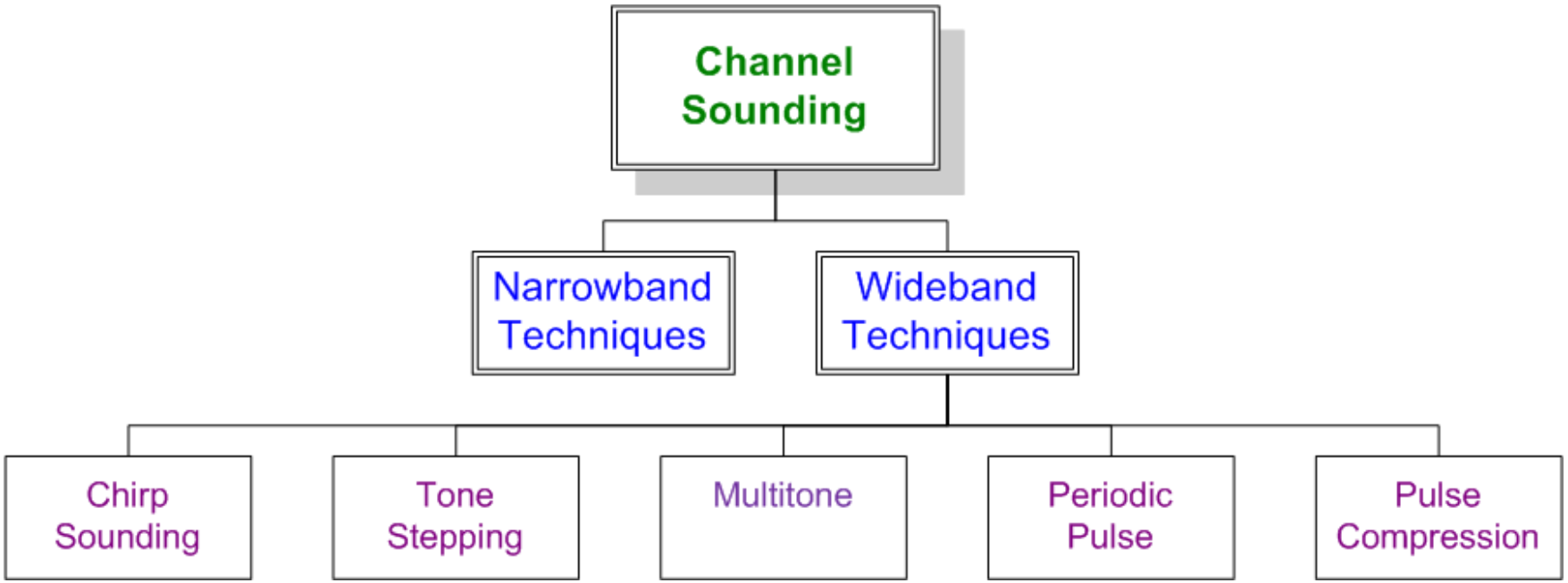
Where Can I Obtain the Input Parameters?

- We can use published models such as the COST series
- We can measure the channel
- We call measuring a communication channel "Channel Sounding"



Example of Measured Impulse Responses

Channel Sounding Techniques



Two main design goals for any sounding system: **real-time processing and real-time recording**

Pulse Compression Sounding

- Based on the theory of linear systems

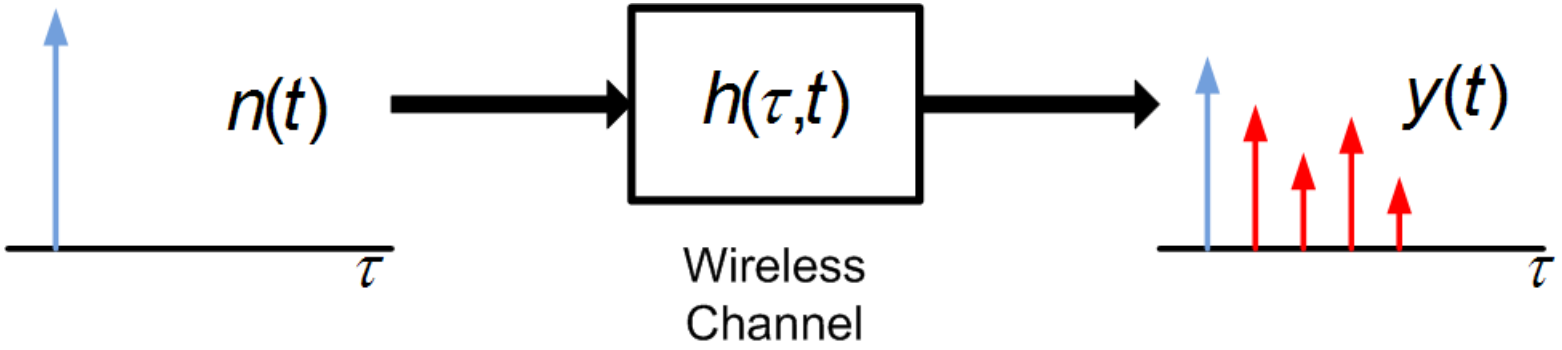
$$E\left[n(t)n^*(t-\tau)\right] = R_n(\tau) = N_o\delta(\tau)$$

$$E\left[y(t)n^*(t-\tau)\right] = E\left[\int h(\lambda)n(t-\lambda)n^*(t-\tau)d\lambda\right]$$

$$= N_0 h(\tau)$$

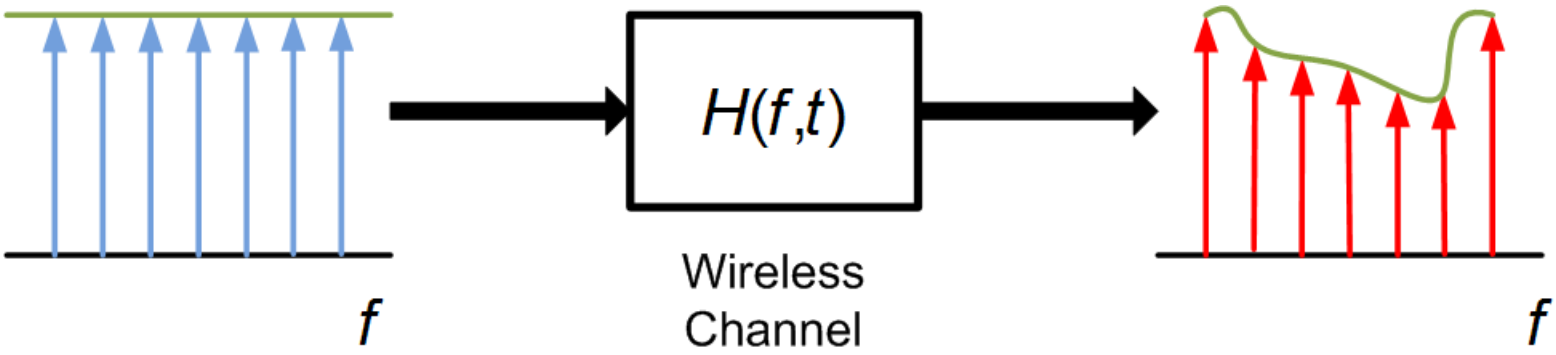
- Uses white noise approximation: maximum length sequences (MLS)
- Similar spectrum and bandwidth to bpsk (double-sided)
- Resolution given by “chip” period, and dynamic range by sequence length $20\log(N)$

Pulse Compression Techniques



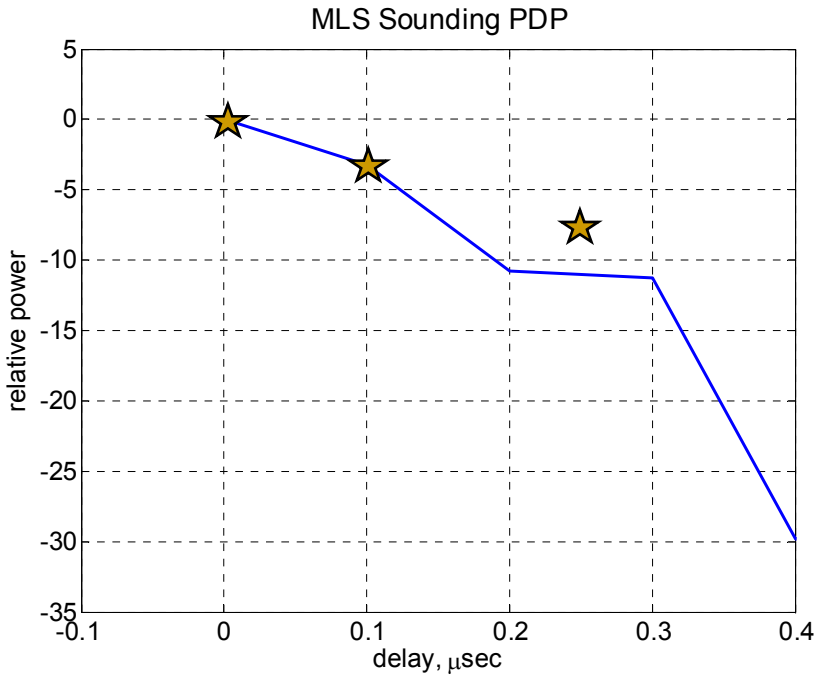
- Best dynamic range
- Double-sided spectrum: real signal transmitted
- “Wastes” half RF bandwidth
- Requires two samples to reconstruct

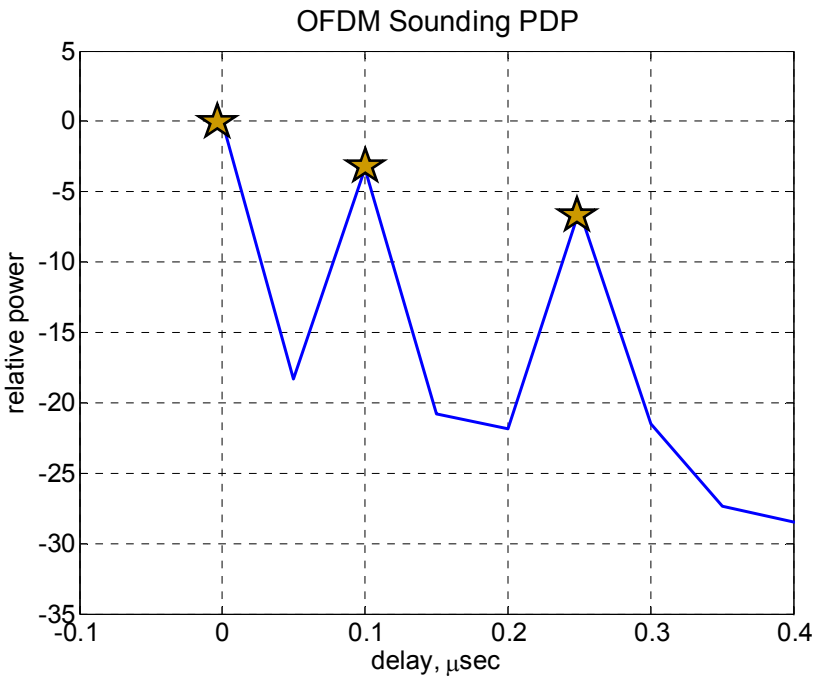
Multitone (OFDM) Sounding



- Send equal amplitude subcarriers through channel
- Obtain channel frequency response
- IFFT gives the channel impulse response
- Uses full RF bandwidth: twice the time resolution as Pulse Compression

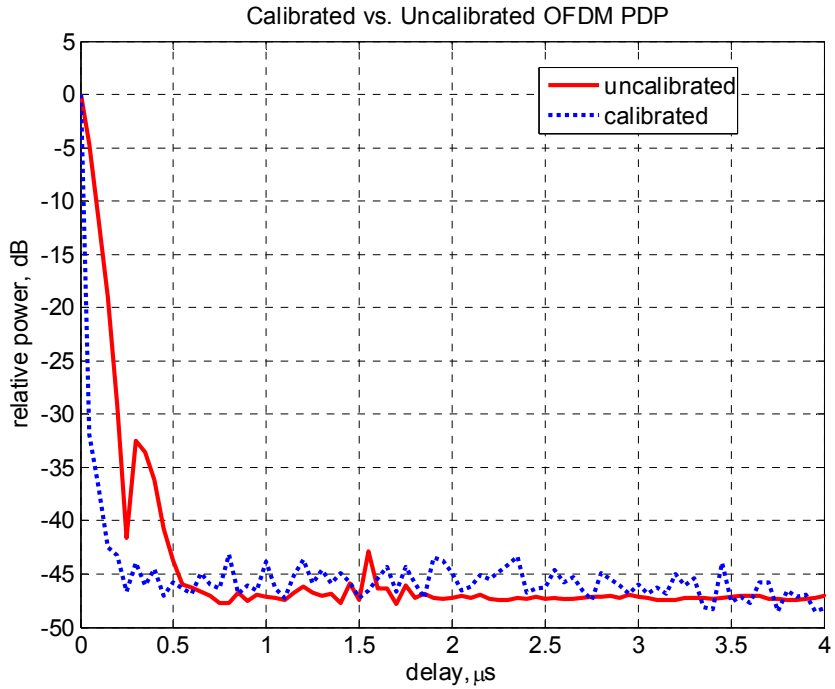
Time Resolution Difference





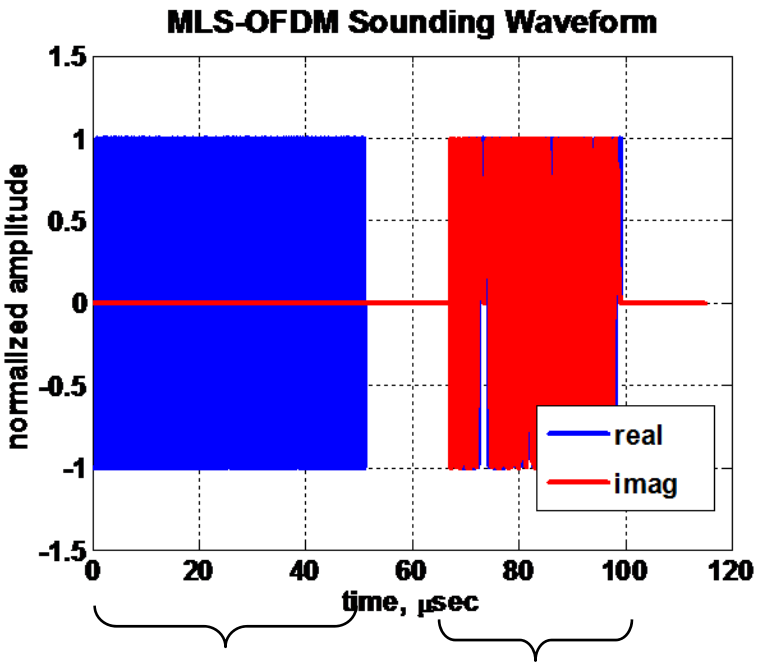
- MLS vs. OFDM time resolution response for a three-tap static channel with delay of 0, 100, and 250 ns and power settings of 0, -4, and -7 dB respectively

OFDM Sounding System Calibration Requirement



- Dynamic range depends on system frequency response
- It is necessary to obtain the cumulative or combined frequency response of all the elements in the communication system

Combined Sounding Waveform



MLS Sequence Length	511 samples
OFDM FFT Length	512 samples
T_c	50 ns
T_{rp}	115.1 μs
Maximum Path Length	34.53 km
Maximum Doppler Frequency	± 4.344 kHz

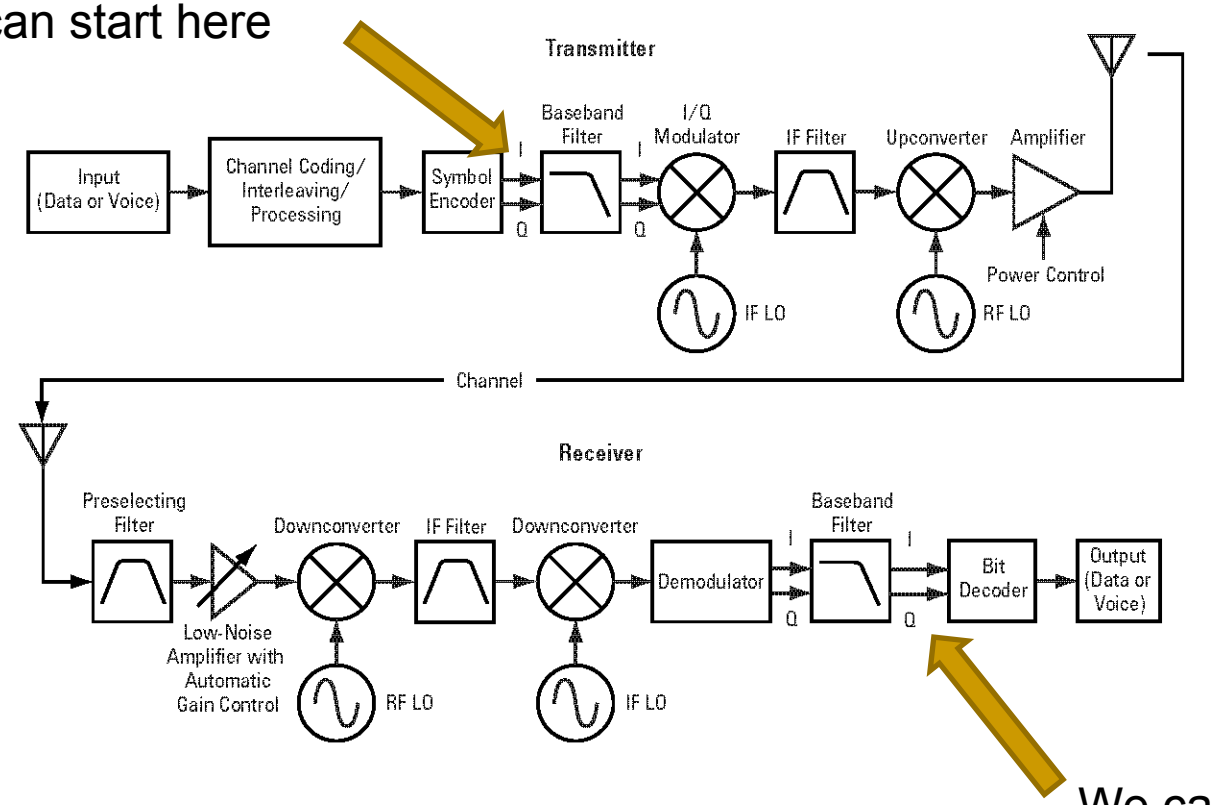
- We used the MLS part to obtain the PDP and to synchronize the OFDM part
- We used the OFDM part to obtain the Doppler spectra

How Do We Design a Channel Sounder?

- If our objective is to sound a channel to generate a channel model, we focus on real-time recording for post processing
- We can use a software radio based architecture
- The design objective is to record In-Phase and Quadrature (I/Q) baseband samples for post-processing
- The Analog-to-Digital (ADC) and Digital-to-Analog (DAC) converters are the defining elements

General Architecture of a Digital Radio

We can start here

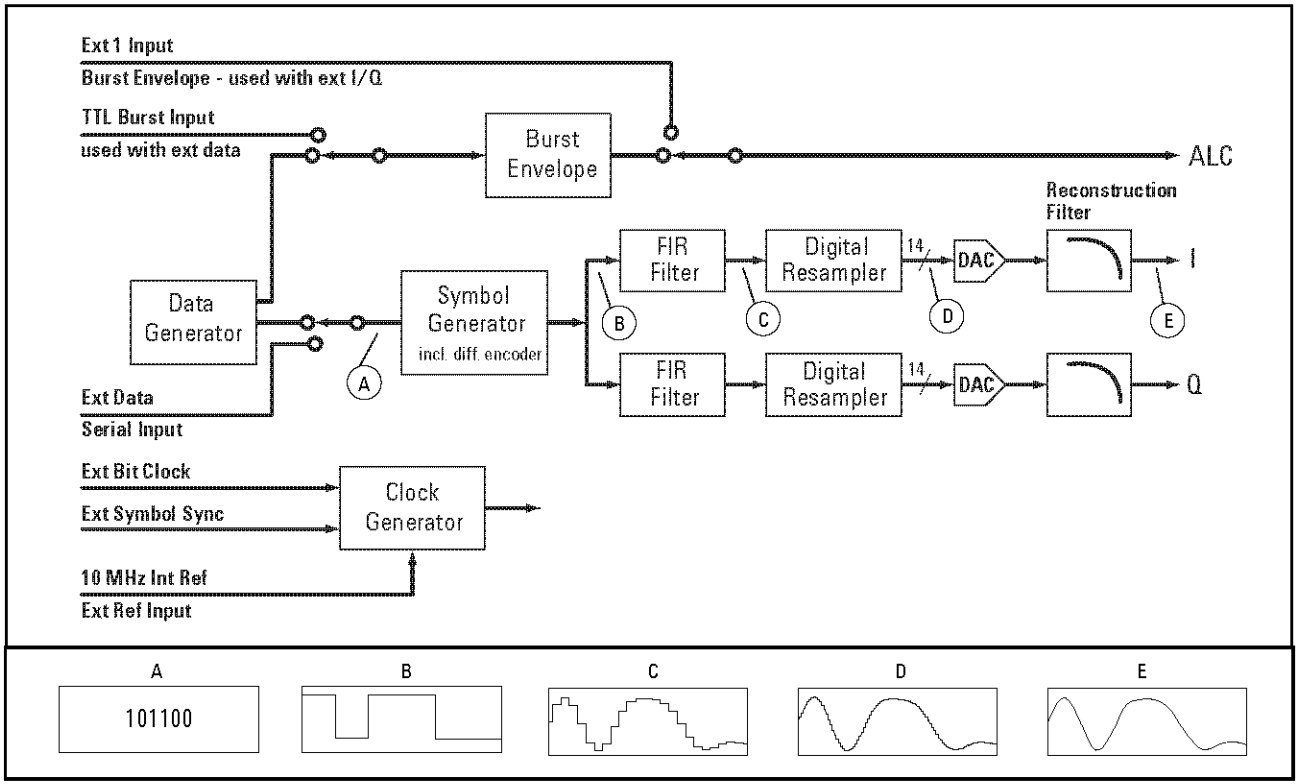


We can end here

Agilent Application Notes 5968-3579E, 5988-6788EN, and 5966-4096E

Digital Transmitter

This is the block diagram of an Agilent ESG 4438C arbitrary waveform generator

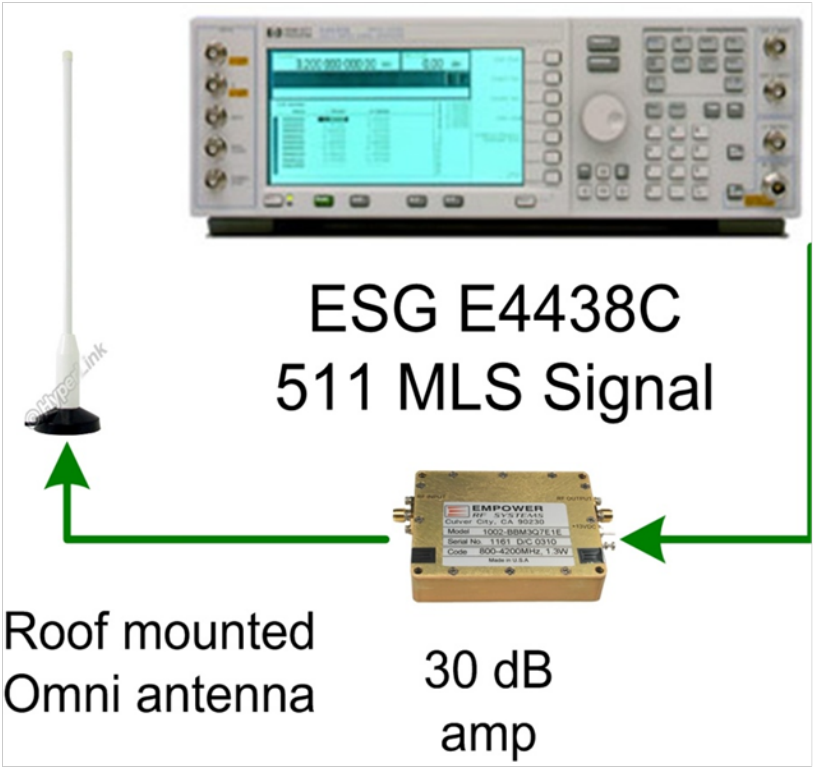


Many of the blocks may be done in a PC

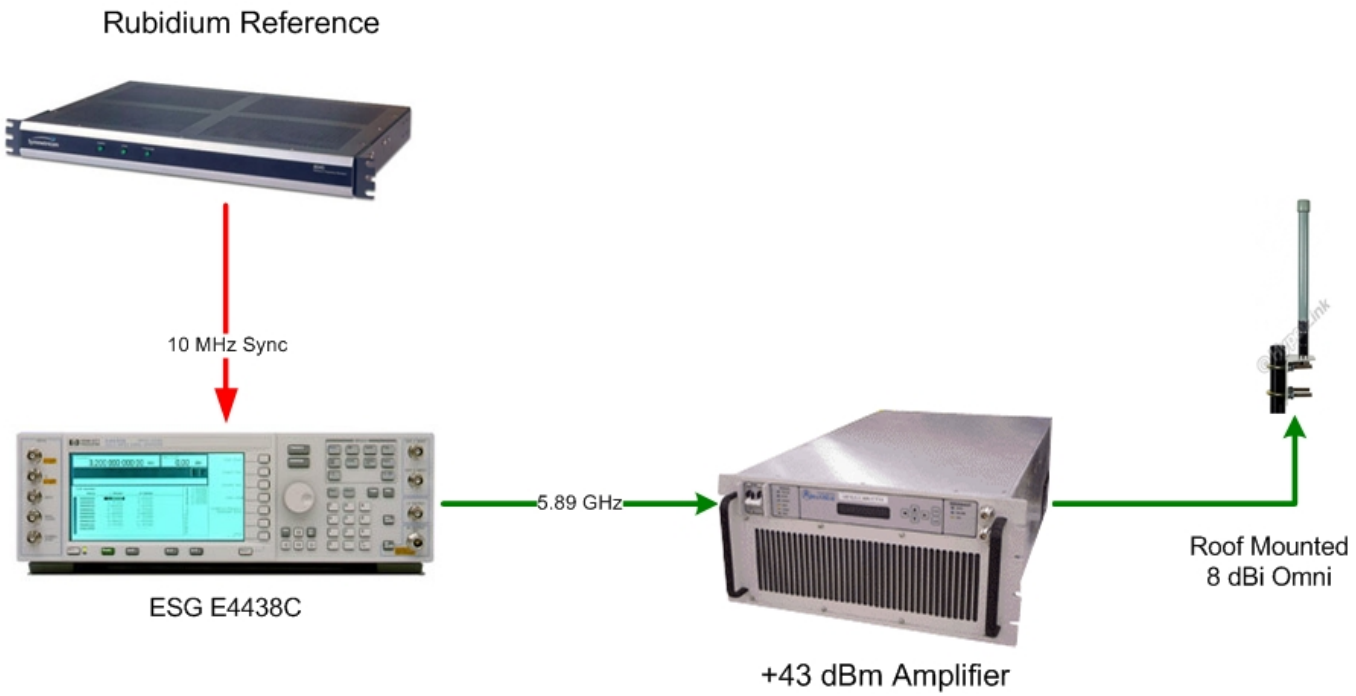
Agilent Application Notes 5968-3579E, 5988-6788EN, and 5966-4096E

2.4 GHz Transmitter Example

Length MLS	511
T_c	50 ns
3 dB BW	20 MHz
T_{rp}	25.5 μs
Maximum Path Length	7.65 km
Maximum Doppler Frequency	19.5 kHz

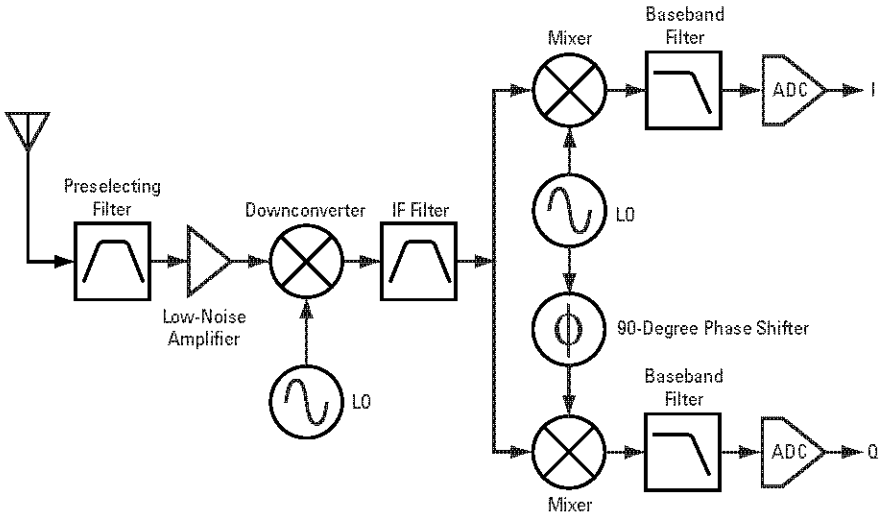


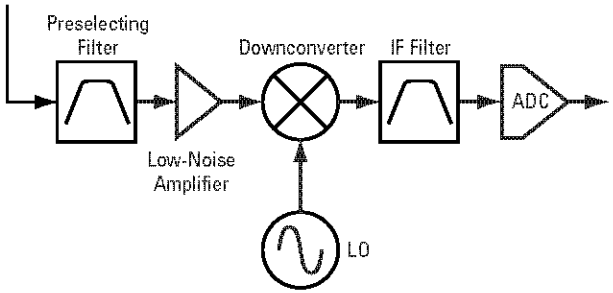
5.9 GHz Transmitter Example



- This time we are using Rubidium reference clocks
- We also have a substantial increase in output power

We Have Two Options for the Receiver



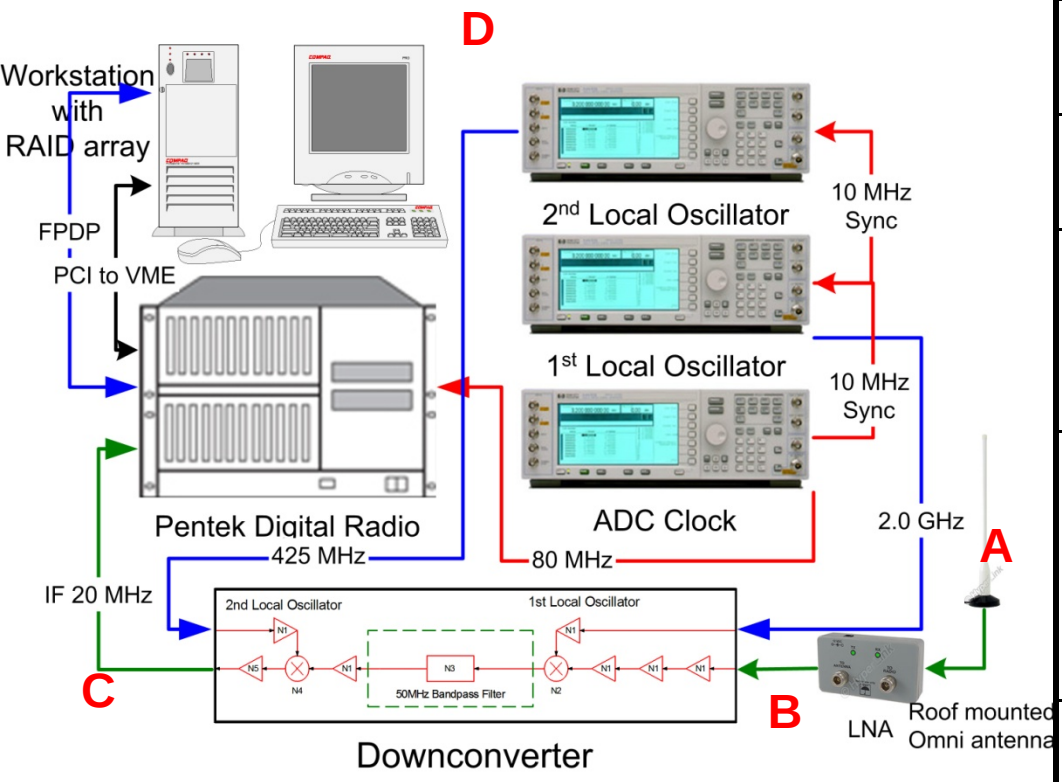


We can sample all the way to baseband: Two ADCs

Or we can sample the intermediate frequency (IF) and finish the down-conversion in the digital domain: One ADC

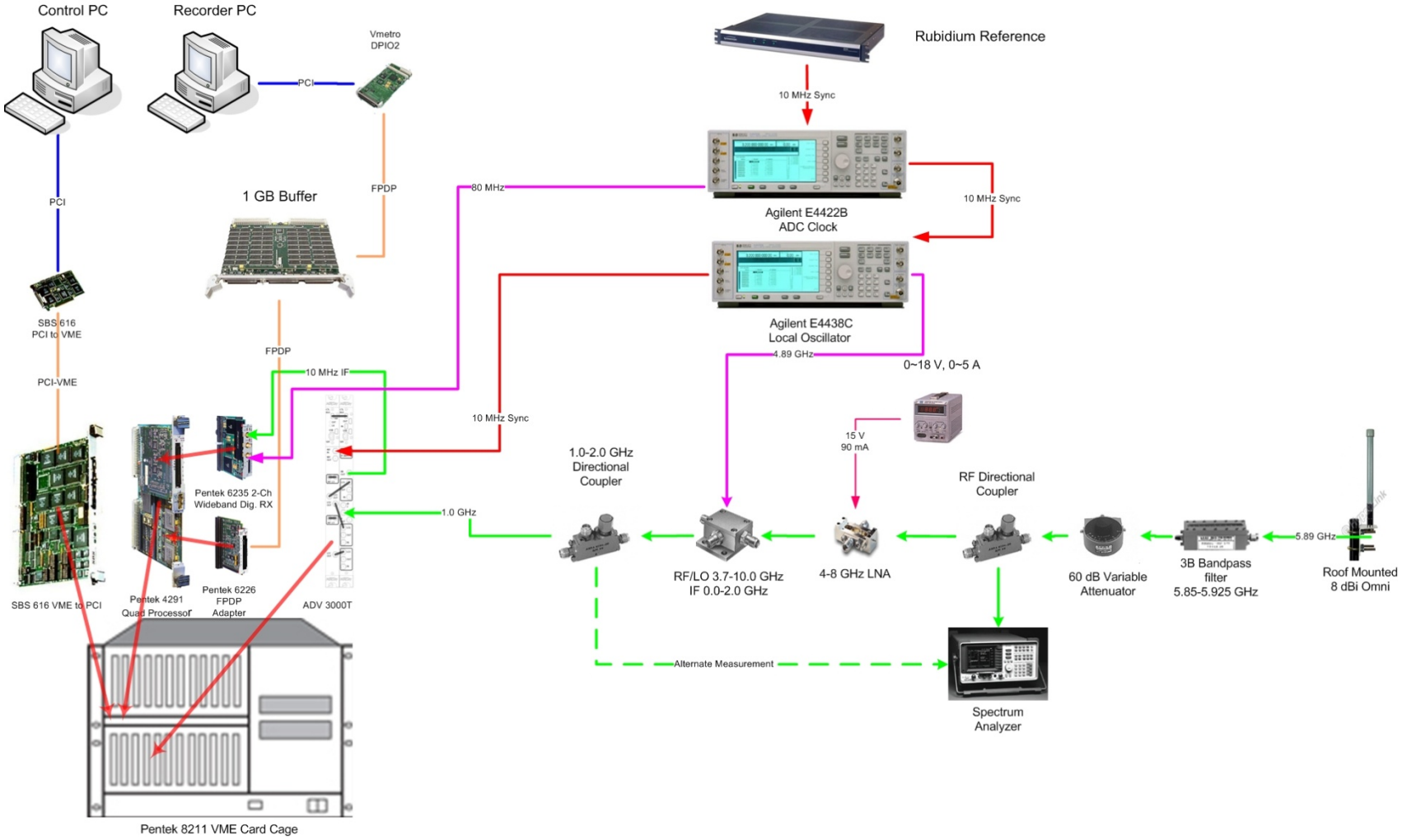
Agilent Application Notes 5968-3579E, 5988-6788EN, and 5966-4096E

2.4 GHz Receiver Example



1st IF	445 MHz
2nd IF	20 MHz
IF Filter BW	46 MHz
ADC	12 bit 80 MHz
Data Rate	20×10^6 complex samples
Recording Speed	80 Mbytes/s

5.9 GHz Receiver Example



Today's Technology

- Recording
  - Since the introduction of the PCI-E bus, direct to hard drive recording speed keeps increasing
  - The latest specification for a RAID system is 1.2 GB/s (300 Mega complex samples per second [four bytes]) and up to 512 TB
  - Assuming that we use the four bytes per complex sample, we can sound 300 MHz RF bandwidth for a time resolution of 3.33 ns
- ADC
  - Texas Instruments ADS5474 is a 400 MSPS 14 bit ADC

“Off the Shelf” Systems

- National Instruments NI PXIe-5663: 16-bit, 150 MS/s
- “Affordable” Option: Ettus USRP2 software radio system with two 100 MS/s 14-bit ADC
- Pentek RTS 2701: two 125 MS/s 14-bit ADC

Wireless Channel Model Development

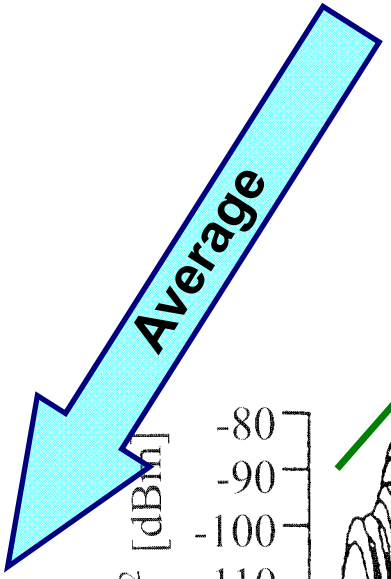
Post Processing Examples

- We will use the next slides to show examples of the type of information you can obtain from the recorded I/Q samples
- We should recall that our objective is to create a useful channel model, i.e., a model to use with the emulator or simulator
- We finish this section with an example of a finished product

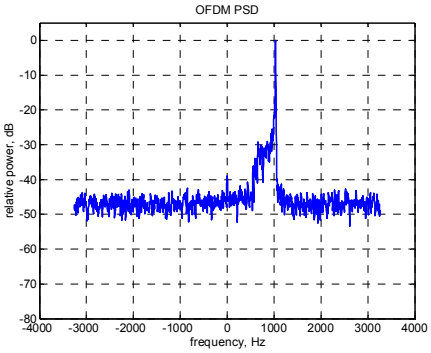
Example of Channel Impulse Response

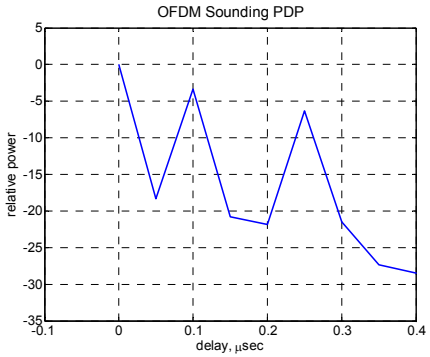
Power Delay Profile

(PDP)



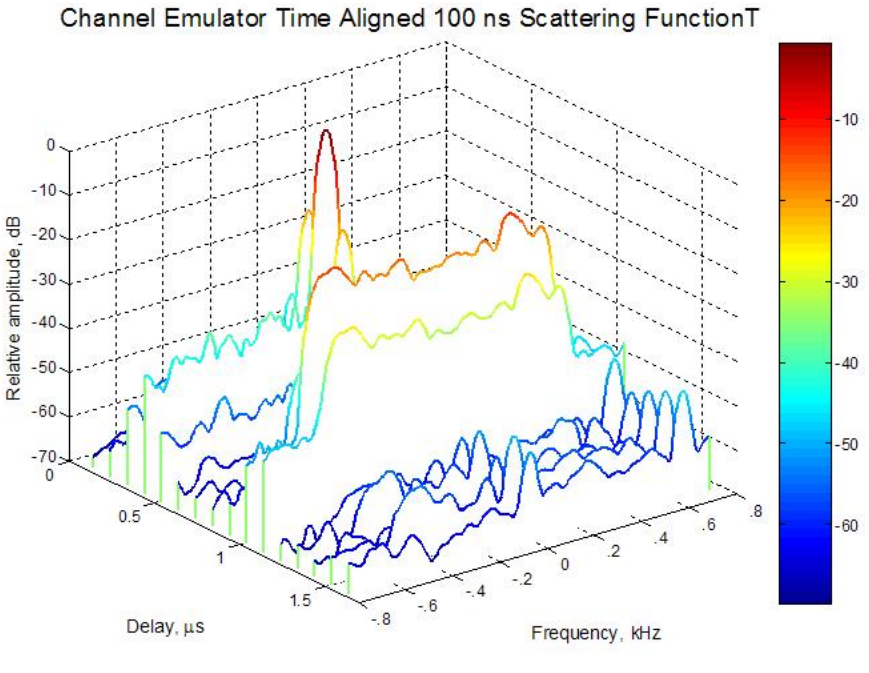
power spectral density (PSD) for fixed delay



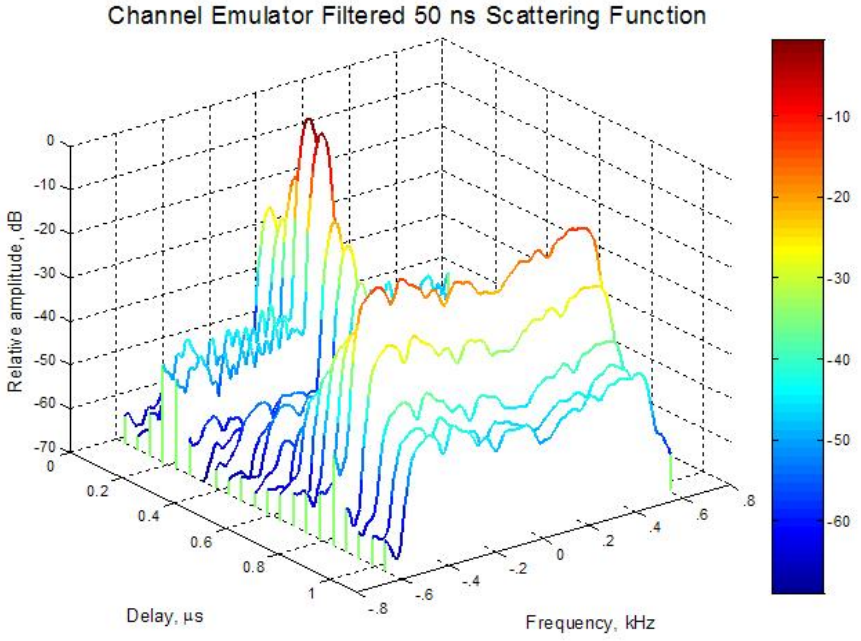


Each line represents and impulse response

Post-Collection System Testing: System's Performance Through Channel Emulator

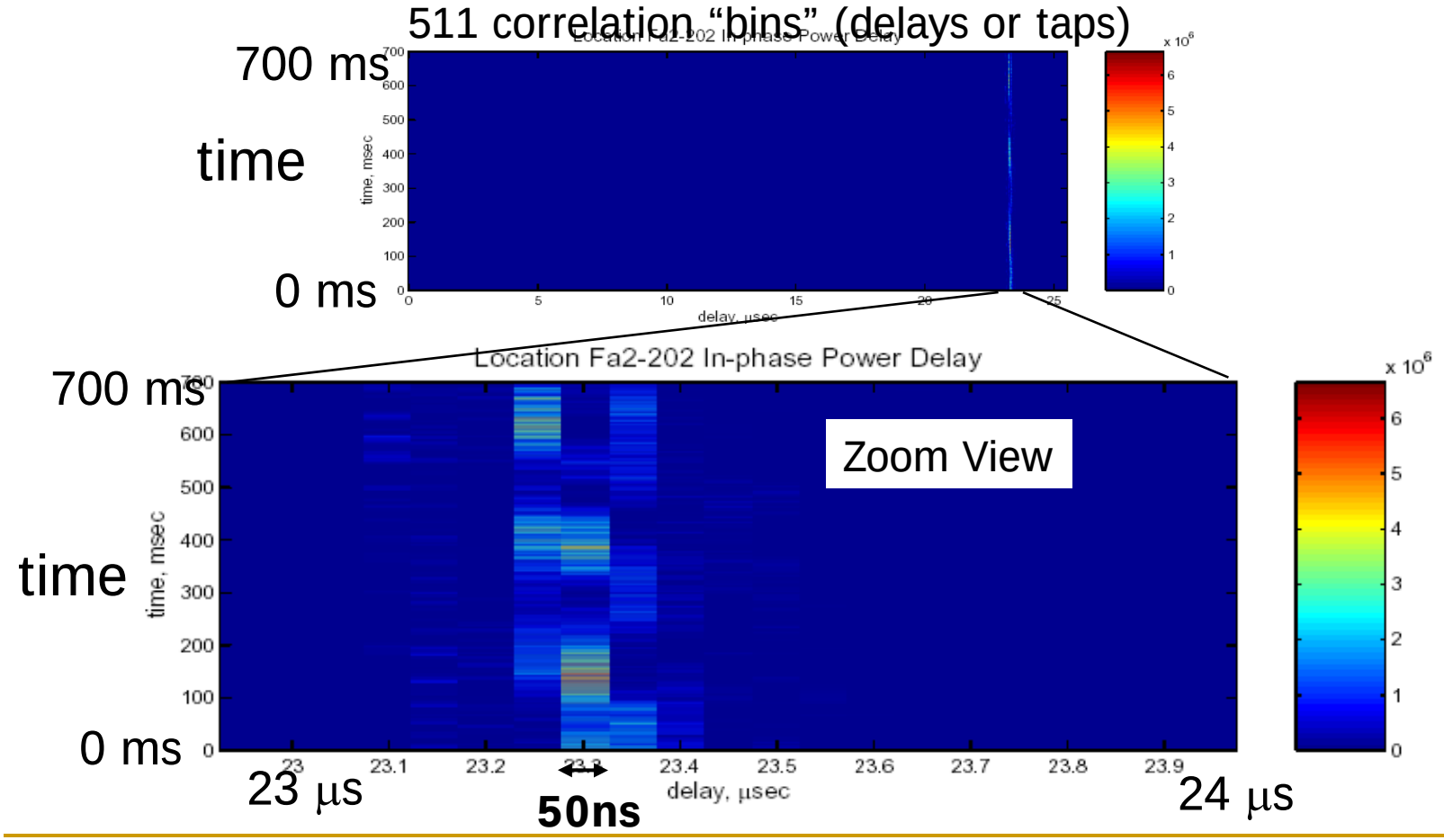


Simulated 50 ns



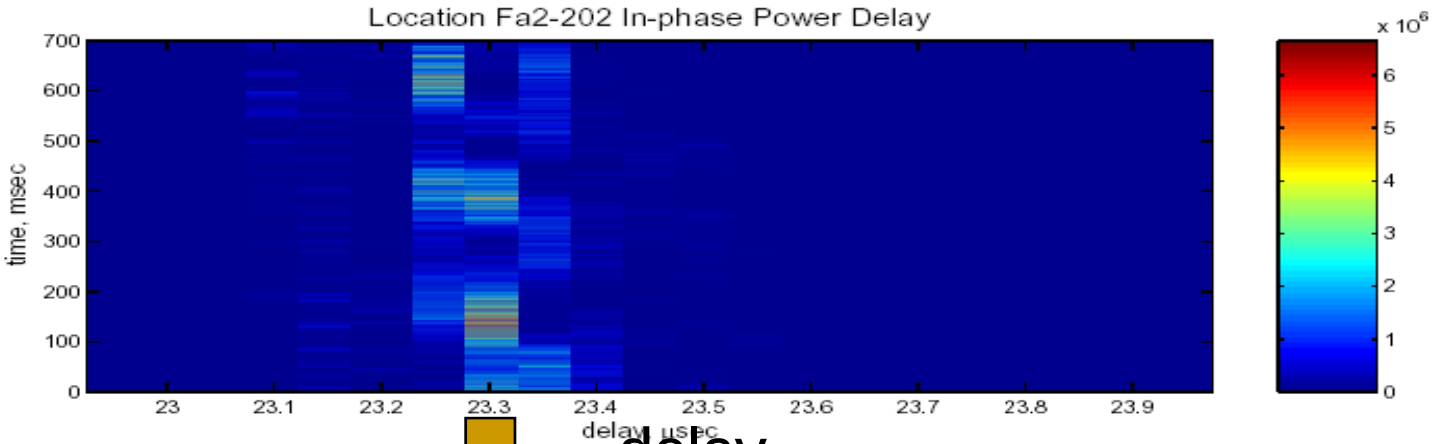
Time aligned 100 ns vs. Filtered 50 ns

Example Matrix (I Channel)

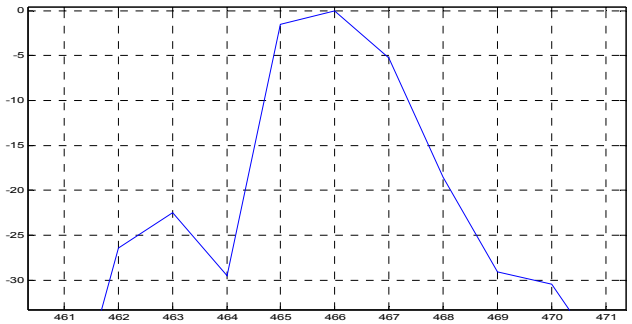


Power Delay Profile

time



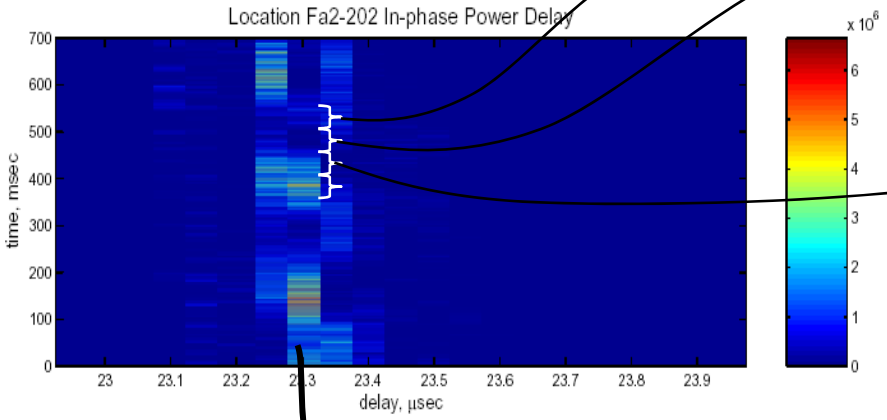
delay

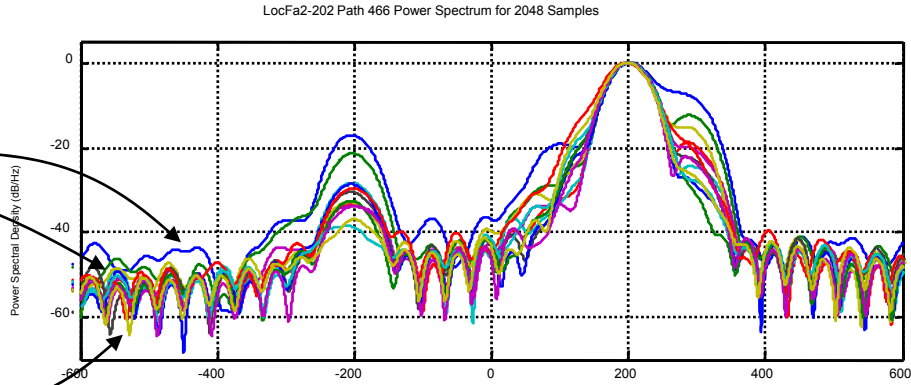


Average magnitude squared of column elements
to get power per bin

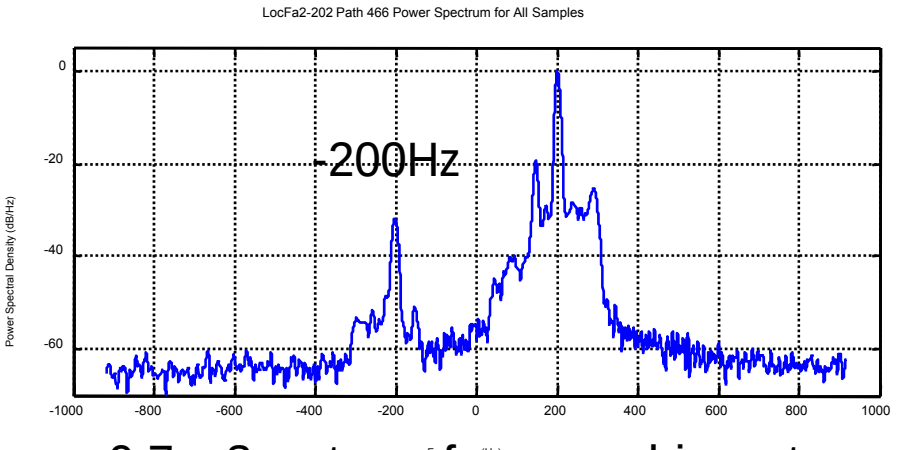
Doppler Spectrum Estimation

Welch's spectral estimate performed on 50ms segments of one bin to see how spectrum changes with time





50ms spectra from one bin or tap

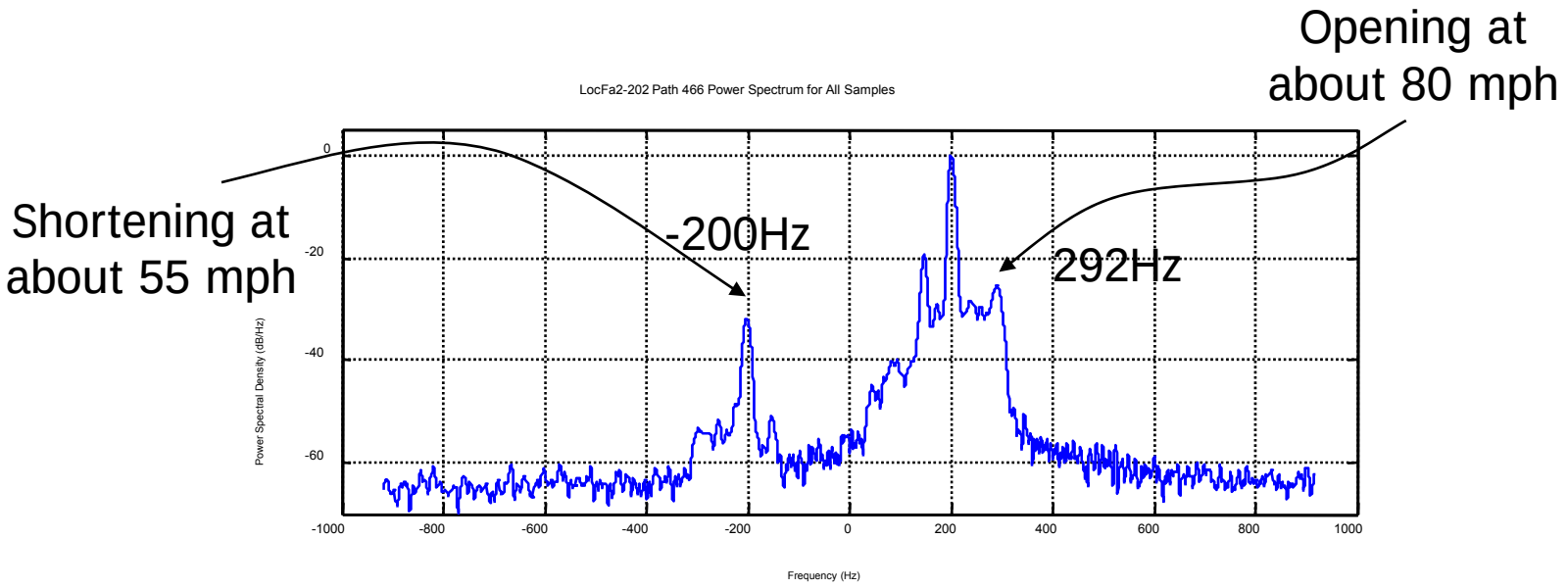


0.7 s Spectrum from one bin or tap

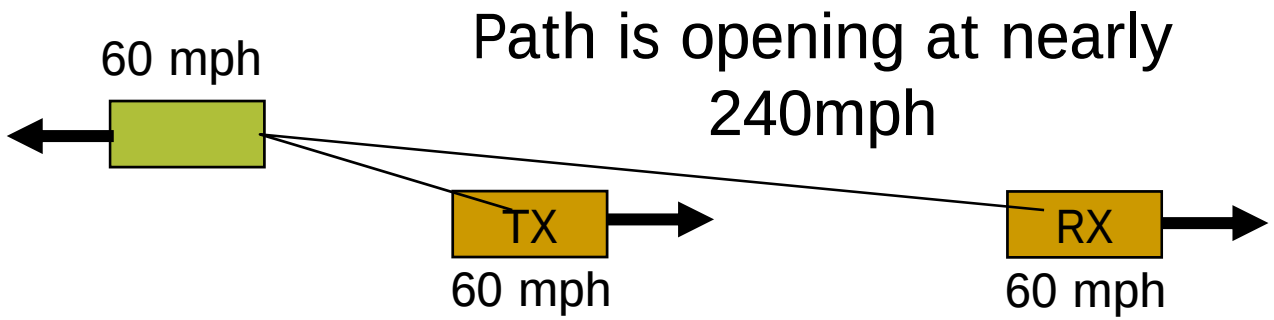
Welch's spectral estimate performed on whole 0.7 seconds of one bin

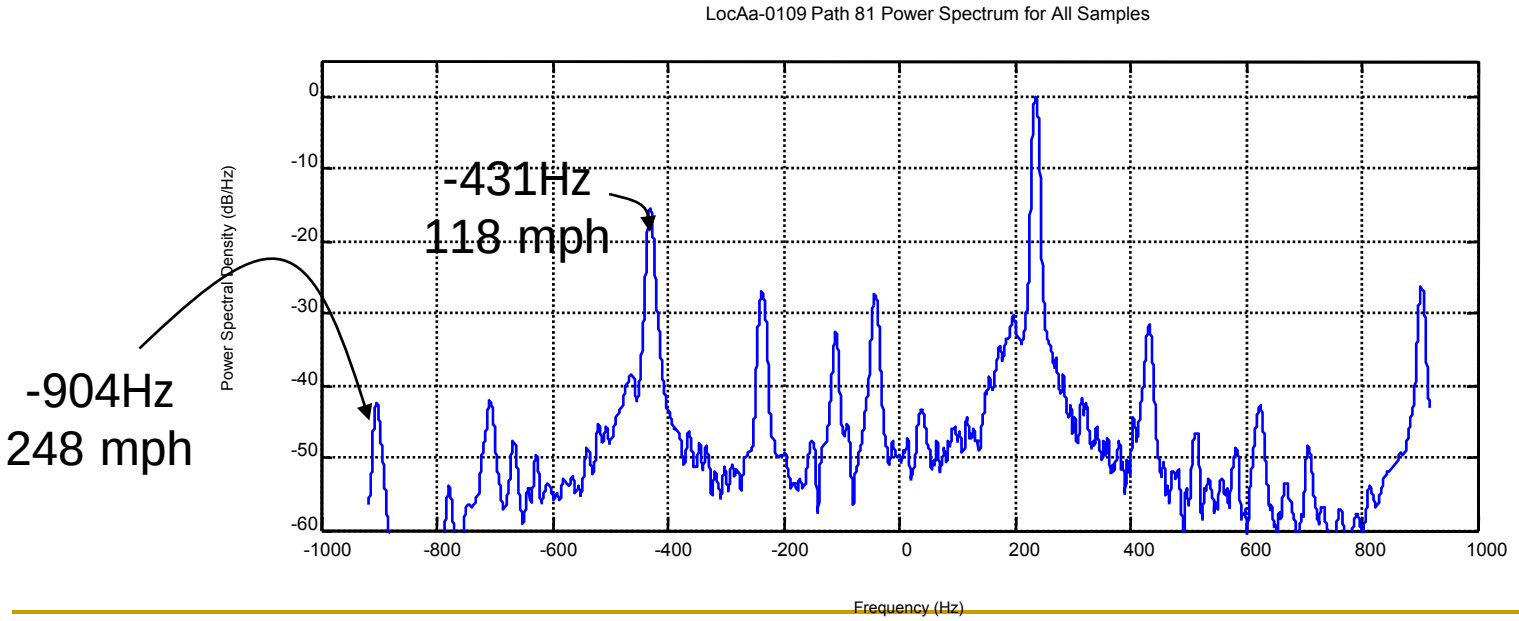
Rate of Path Length Change

- At 2.445 GHz, we can find the rate at which a path is changing length in mph by dividing the Doppler frequency in Hz by 3.64

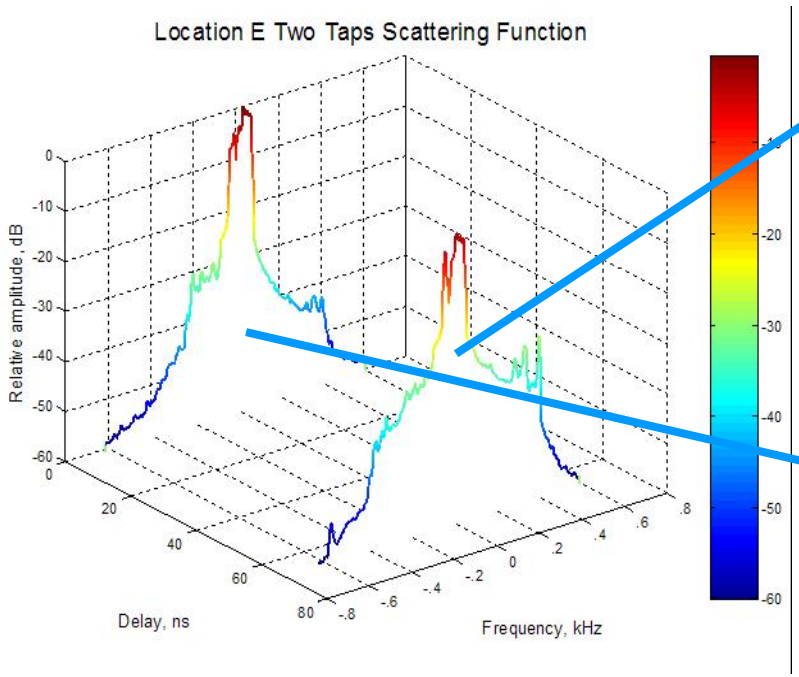


High Rates of Path Length Change

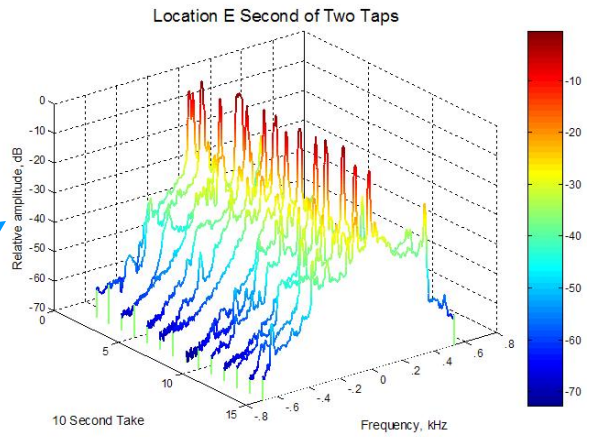




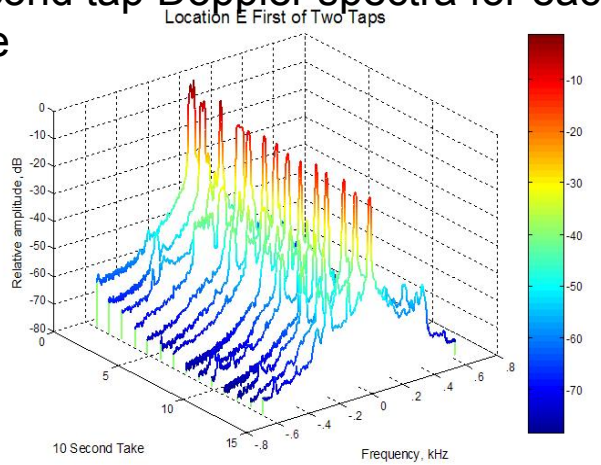
Two Path Statistical Model for Expressway



Two path statistical model



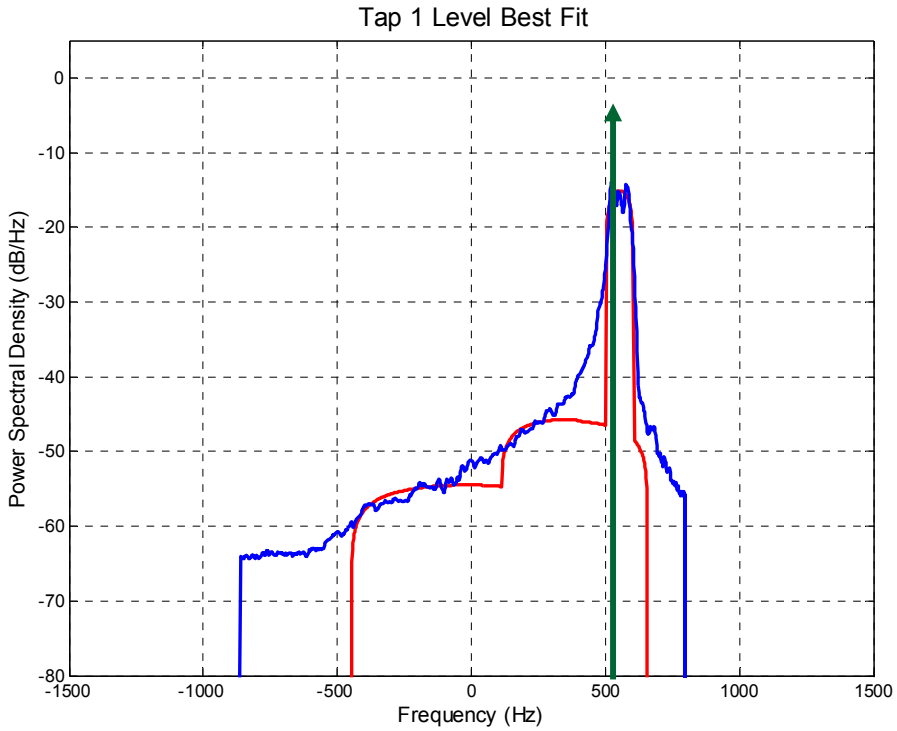
Second tap Doppler spectra for each 10 s take



First tap Doppler spectra for each take 10 s take

Example of a Complex Tap Spectrum

- Channel emulators have 6, 12, or 24 paths depending on price
- Our objective is to match the tap spectrum with the minimum possible of paths



Very complex spectrum requiring three shapes!

Expressway Same Direction Model

Tap No.	Path No.	Tap Power (dB)	Relative Path Loss (dB)	Delay Value (ns)	Rician K (dB)	Freq Shift (Hz)	Fading Doppler (Hz)	LOS Doppler (Hz)	Modulation	Fad. Spec. Shape
1	1	0.0	-1.4	0	23.8	-55	1407	-60	Rician	Round
1	2		-5.6	1	n/a	-20	84	n/a	Rayleigh	Round
2	3	-11.2	-14.2	100	5.7	-56	1345	+40	Rician	Classic 3 dB
2	4	0	-14.2	101	n/a	0	70	n/a	Rayleigh	Round
3	5	-19.0	-19.0	200	n/a	-87	1358	n/a	Rayleigh	Classic 6 dB
4	6	-21.9	-21.9	300	n/a	-139	1397	n/a	Rayleigh	Classic 3 dB
5	7	-25.3	-27.9	400	n/a	60	1522	n/a	Rayleigh	Classic 6 dB
5	8		-30.8	401	n/a	-561	997	n/a	Rayleigh	Classic 3 dB
6	9	-24.4	-24.4	500	n/a	50	1529	n/a	Rayleigh	Round
7	10	-28.0	-28.0	600	n/a	13	1572	n/a	Rayleigh	Round
8	11	-26.1	-31.5	700	n/a	-6	1562	n/a	Rayleigh	Classic 6 dB
8	12		-28.1	701	n/a	4	81	n/a	Rayleigh	Round

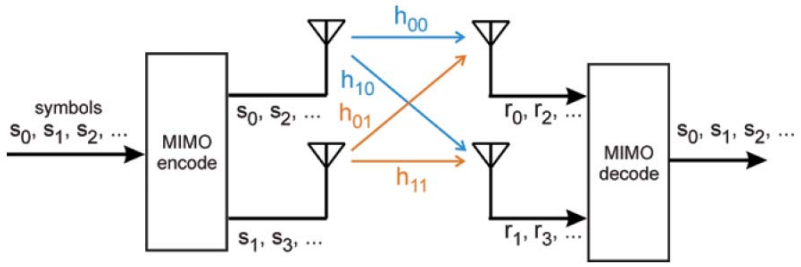
Expressway Same Direction Model Notes (complement to table)

1. Taps 1, 2, 5 and 8 have composite spectra. Each tap comprises two paths. The first two taps each have Rician and Rayleigh paths. The overall K factor is 4.0 dB for Tap 1 and -1.8 dB for Tap 2. Tap 8 comprises two Rayleigh paths. All paths associated with a composite Doppler spectrum have excess delays differing by 1ns. This is to ensure that the channel emulator creates them as separate paths. Because of its limited bandwidth, the unit under test will perceive two paths that differ in delay by only 1 ns as having essentially the same delay.
2. “n/a” means “not applicable.”
3. This channel is normalized so that the first tap power is 0 dB.
4. The parameters are named according to the Spirent SR5500 TestKit control software.
5. The SR5500 parameters LOS AOA and LOS Doppler are interdependent.
6. The SR5500 parameters Fading Doppler and Fading Doppler Vel. are interdependent.

MIMO Channel Sounding

MIMO Extension: 2x2 Example

Transmitter and Receiver MUST be synchronized!



$$\begin{bmatrix} r_1 \\ r_2 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} s_1 \\ s_2 \end{bmatrix}$$

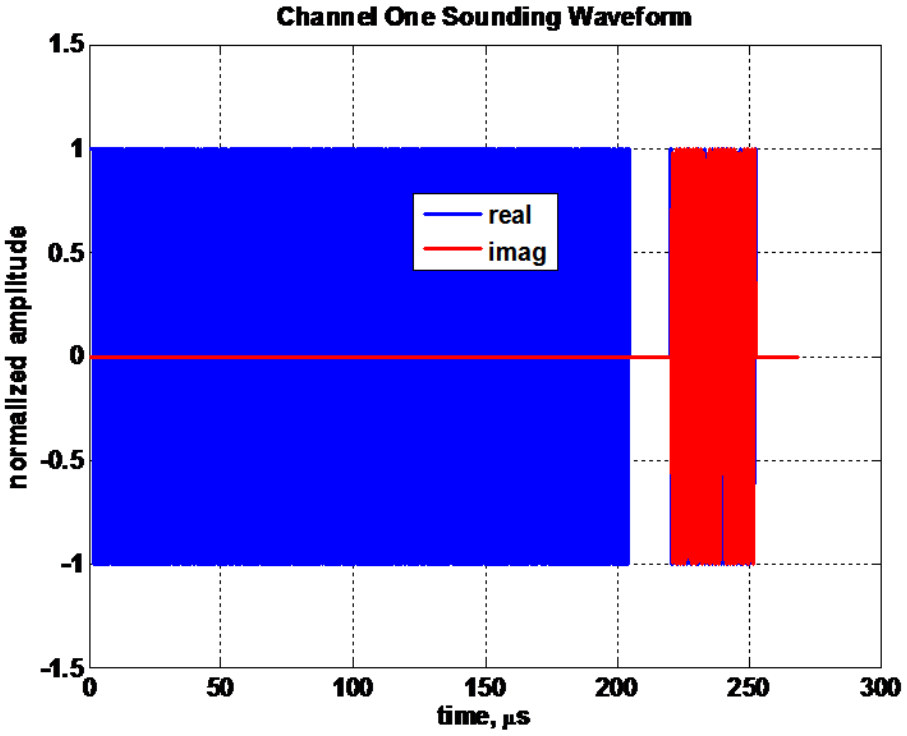
PULSE COMPRESSION:
Use sequences with good autocorrelation and cross-correlation properties: GOLD Sequences

MULTITONE:
Alternate each transmitted signal in the subcarriers, e. g. odd subcarriers for TX1 and even subcarriers for TX2

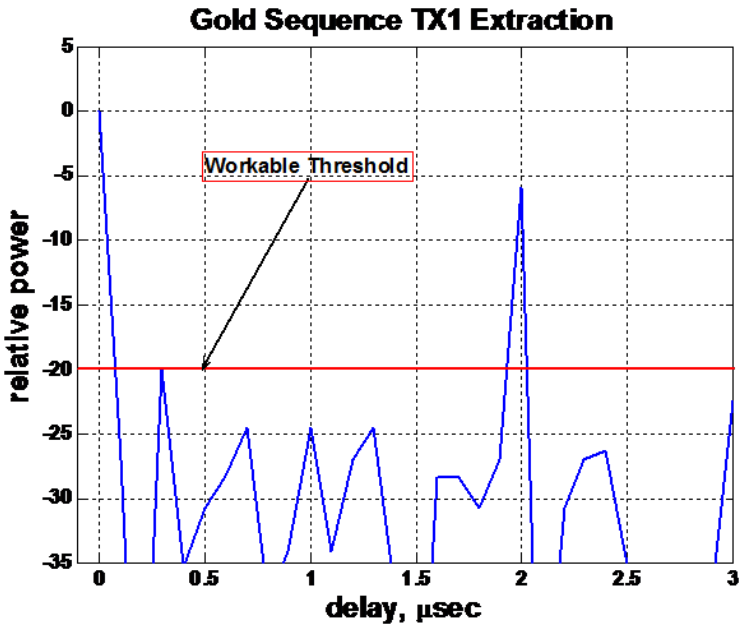
Agilent Application Note 5989-8973E

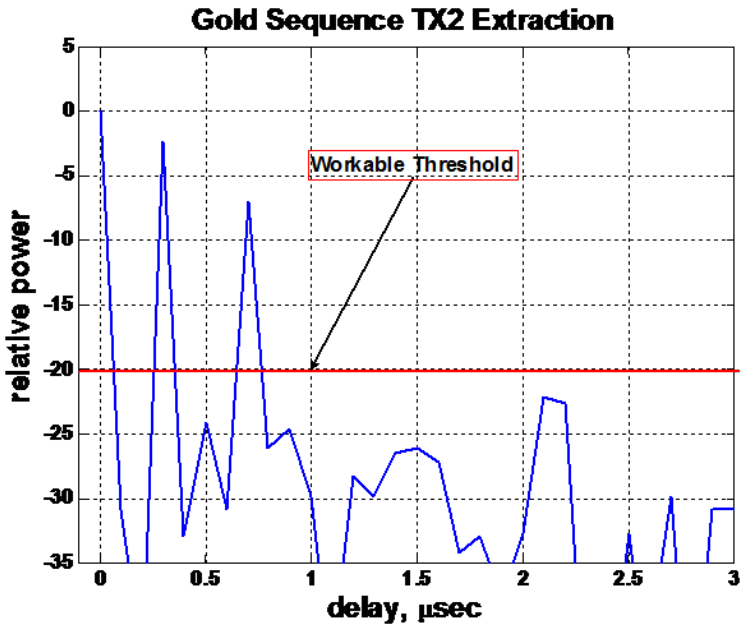
MIMO Sounding Waveform

- Three sections:
  - A length 2,047 Gold Sequence with a 100 ns chip period
  - A 512 FFT OFDM signal with a 128 guard band and a 50 ns period
  - Two null segments of length 320 and 50 ns period separating the OFDM signal
- 268.7 μs total waveform period for a ±1.86 kHz maximum Doppler frequency



Gold Sequence Segment Performance



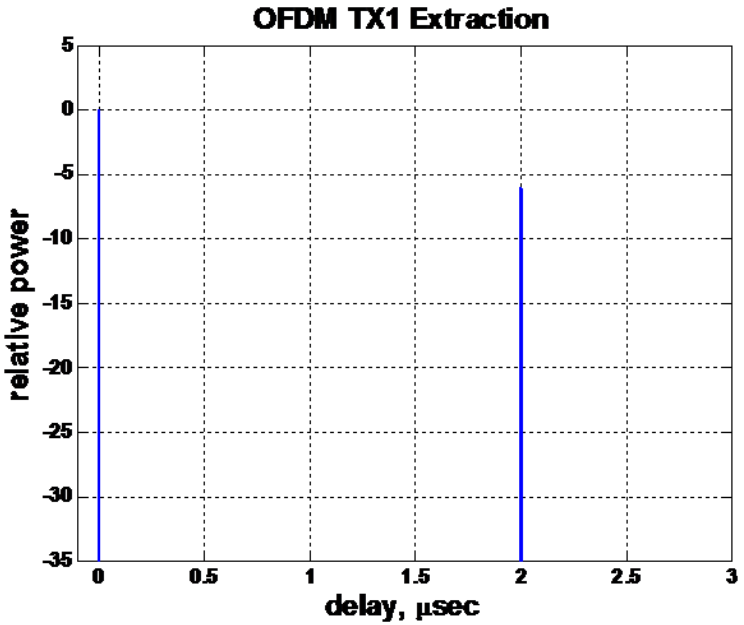


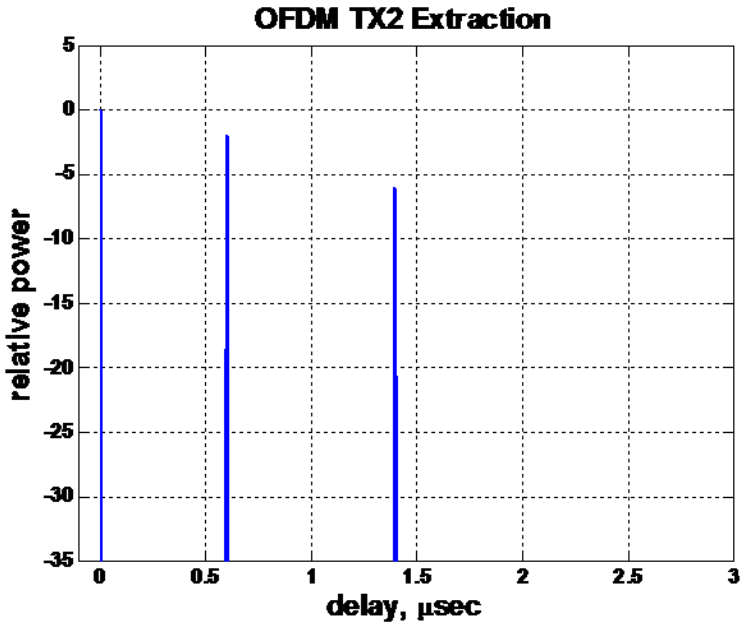
TX1: ([0 ns, 0 dB], [2,000 ns, -6 dB]) and TX2: ([0 ns, 0 dB], [150 ns, -2 dB], [750 ns, -6 dB]) simulation example

We use the Gold sequences primarily for synchronization, but they also provide channel information

We can obtain a 100 ns resolution channel information with 20 dB of dynamic range

OFDM Segment Performance

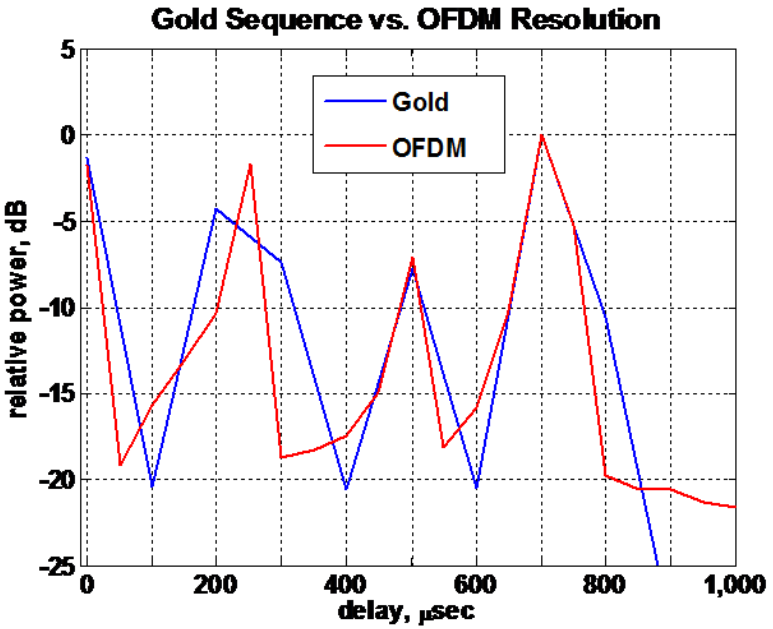




- Same parameters simulation results
- We increase the resolution to 50 ns
- The dynamic range is set by the sounding system performance
- OFDM sounding requires system calibration since its performance is closely tied to system's nonlinearities

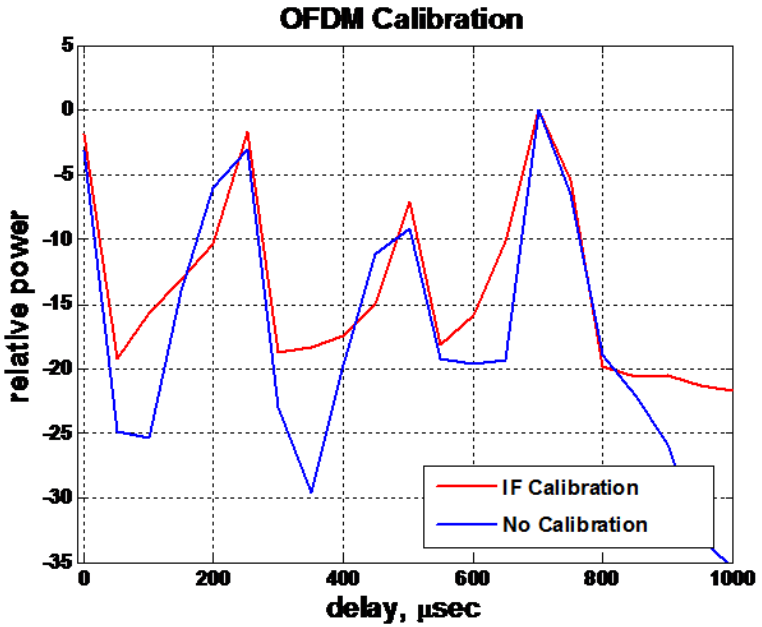
h11 Channel Emulation Results

- We can process approximately 0.55 second segments
- We are showing the TX1 extraction
- We notice the gain in resolution from the OFDM segment @ the 250 ns path

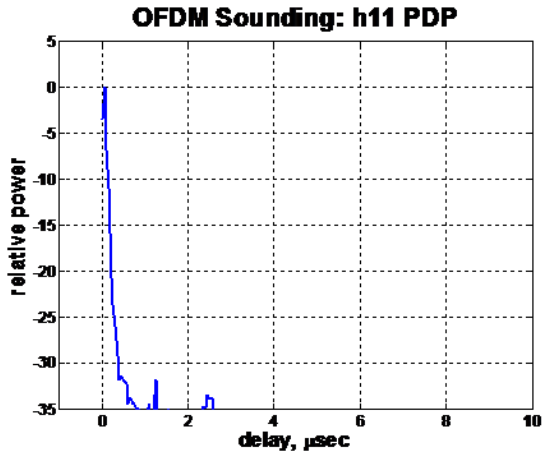


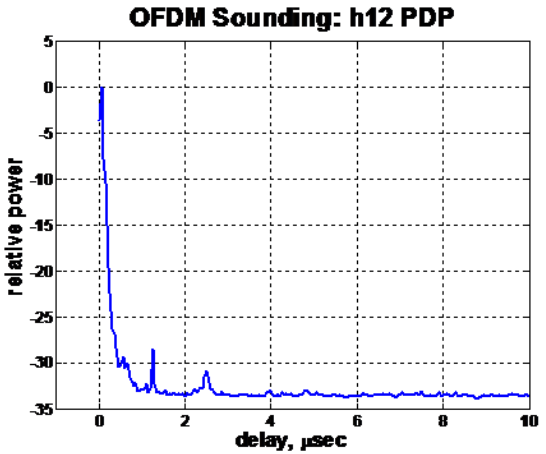
OFDM Calibration

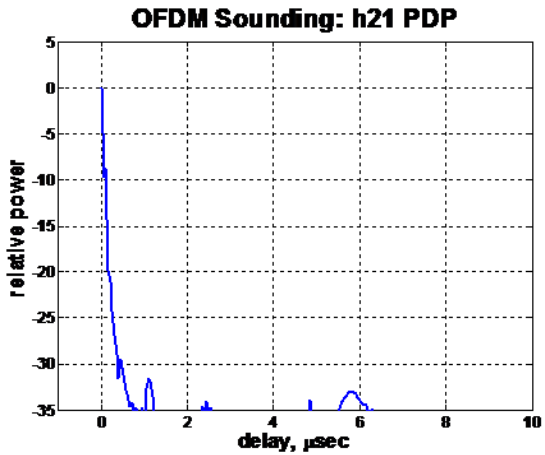
- The system's calibration reduces the signal spreading
- Unfortunately, there is no overall calibration
- The calibration is test specific
- Every element in the path (cables, connectors, etc.) changes the calibration
- For these results, we used the IF calibration, i.e., the most direct recording path
- Even without the exact calibration, we can obtain a better delay resolution

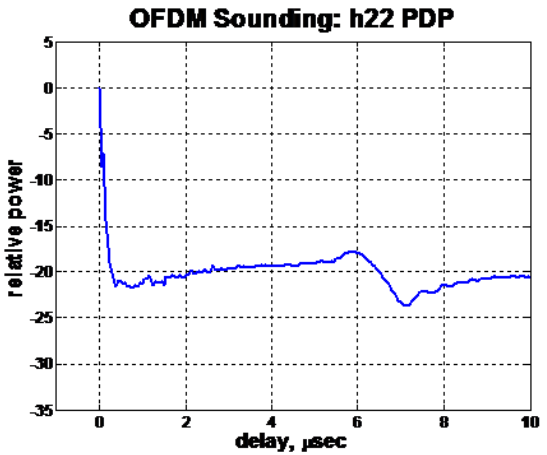


2x2 MIMO VV Mobile OFDM Sounding PDPs for a 0.6 s Segment

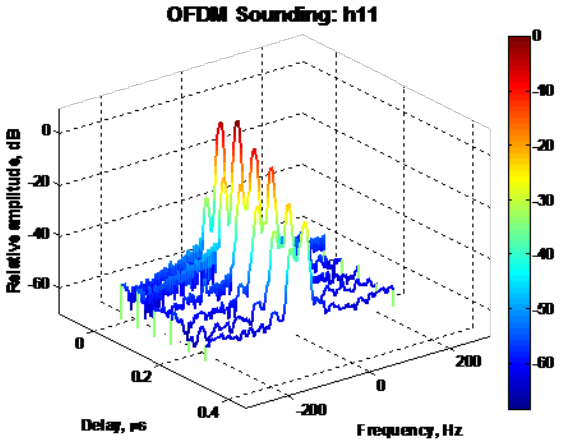


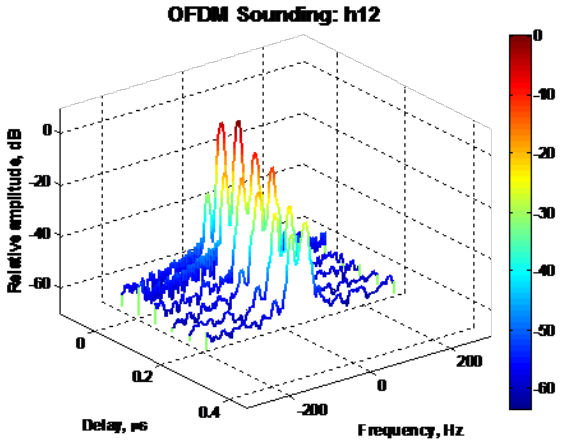


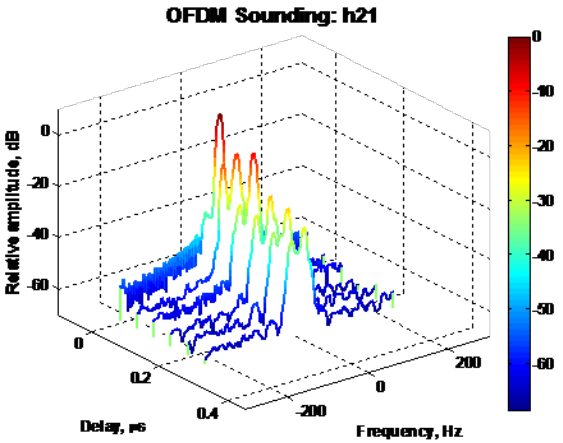


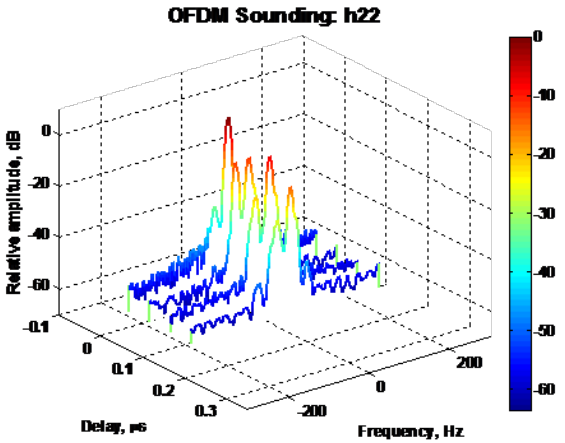


2x2 MIMO VV Mobile OFDM Sounding Scattering Functions for a 0.6 s Segment

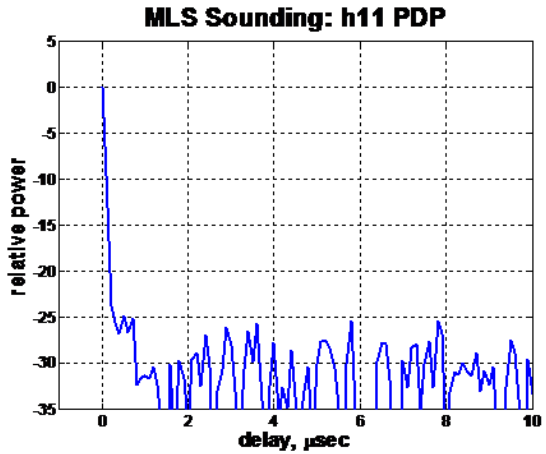


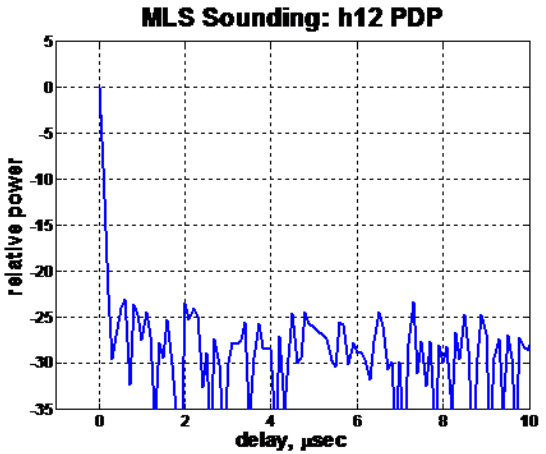


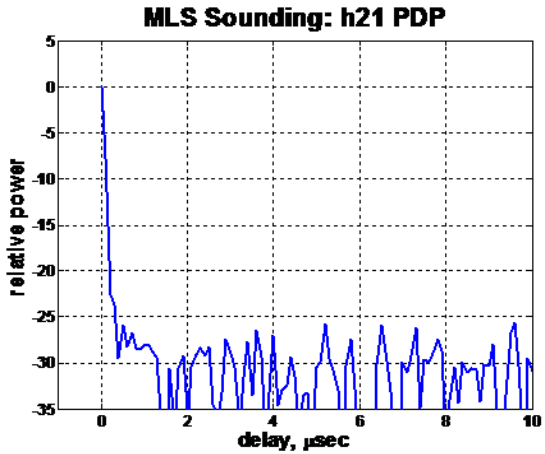


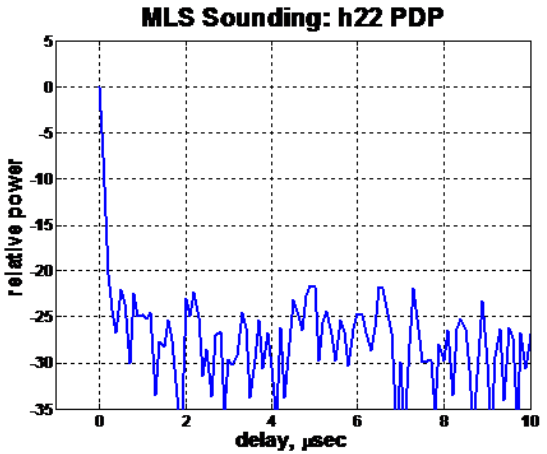


2x2 MIMO VV Mobile MLS Sounding PDPs for a 0.6 s Segment

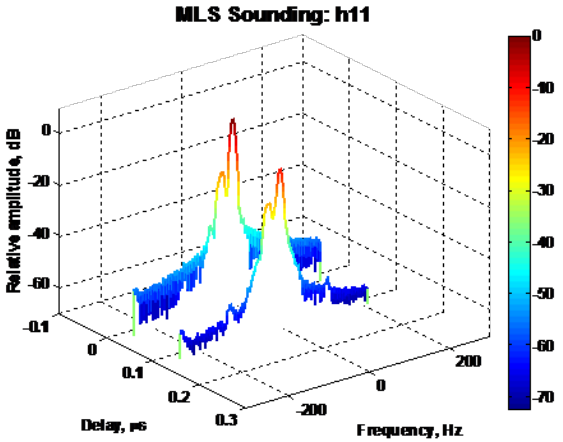


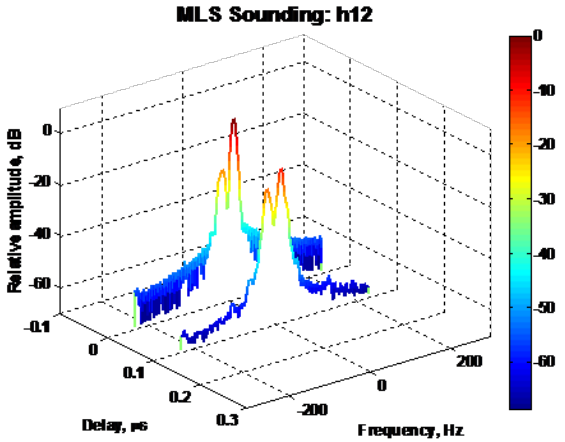


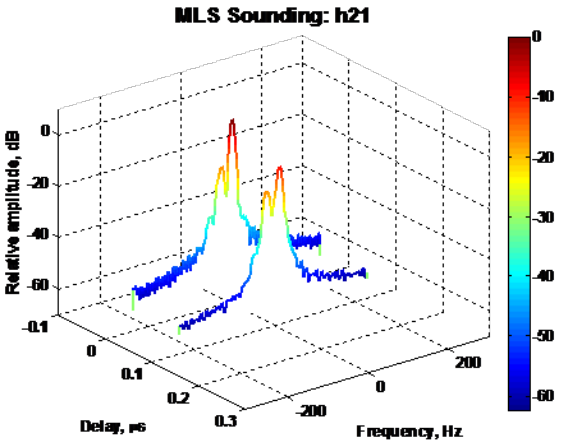


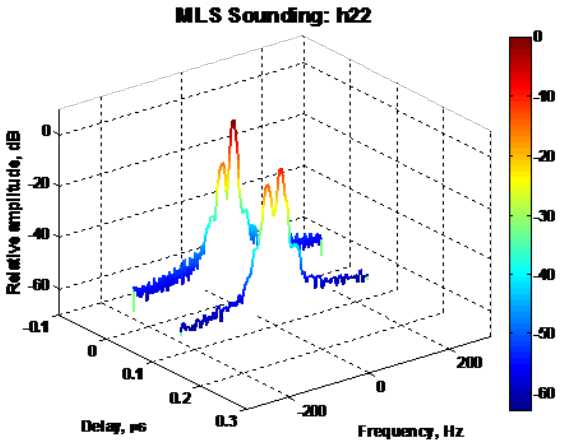


2x2 MIMO VV Mobile MLS Sounding Scattering Functions for a 0.6 s Segment









Thank you!