

A Proposal for IEEE P1451.5, Standard for a Smart Transducer Interface for Sensors and Actuators - Wireless Communication Protocols and Transducer Electronic Data Sheets (TEDS) Formats

Submission Title: [A Proposal for the IEEE 1451.5 Wireless Smart Sensor Standard]

Date Submitted: [28 March 2003]

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Re: [Call for Proposals]

Abstract: [A method for using appropriate open-standard wireless protocols represents the best solution to the immensely diverse requirements for wireless smart sensing applications.]

Purpose: [Response to the Wireless Sensor Working Group Chair's Call for Proposals]

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A Proposal for the IEEE 1451.5 Wireless Smart Sensor Standard

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A Listing of Acronyms & Abbreviations

ACK	Acknowledgement	IT	Information Technology
AES	Advanced Encryption Standard		
AP	Access Point	J2ME	Java 2 Micro-Edition™
BER	Bit Error Rate	MAC	Medium Access Control (Layer)
BPSK	Binary Phase Shift Keying	MCTA	Management CTA
		MIPS	Million Instructions Per Second
CAP	Contention Access Period	MIS	Management Information Systems
CBC-MAC	Cipher Block Chaining Message Authentication Code		
CCA	Clear Channel Assessment	NOC	Network Operation Center
CCK	Complementary Code Keying		
CCM	Counter mode + CBC-MAC	OFDM	Orthogonal Frequency-Division Multiplexing
CFP	Contention Free Period	OOK	On-Off Keying
CRC	Cyclic Redundancy Check	O-QPSK	Offset QPSK
CSMA/CA	Carrier Sense Multiple Access/Collision Avoidance		
CTR	Counter mode	PBCC	Packet Binary Convolutional Coding
CTA	Channel Time Allocation	PHY	Physical Layer
		PN	Pseudo Noise
DBSK	Differential BPSK	PNC	Piconet Controller
DHCP	Dynamic Host Configuration Protocol		
DQPSK	Differential QPSK	QAM	Quadrature Amplitude Modulation
DSP	Digital Signal Processor	QPSK	Quadrature Phase Shift Keying
DSSS	Direct Sequence Spread Spectrum		
		RX	Receiver
F.C.C.	Federal Communications Commission		
FEC	Forward Error Correction	SSL	Secure Socket Layer
FHSS	Frequency Hopped Spread Spectrum		
		TX	Transmitter
GFSK	Gaussian Frequency Shift Keying		
GPRS	General Packet Radio Service	WWW	World Wide Web
GTS	Guaranteed Time Slot		

“Introduction”

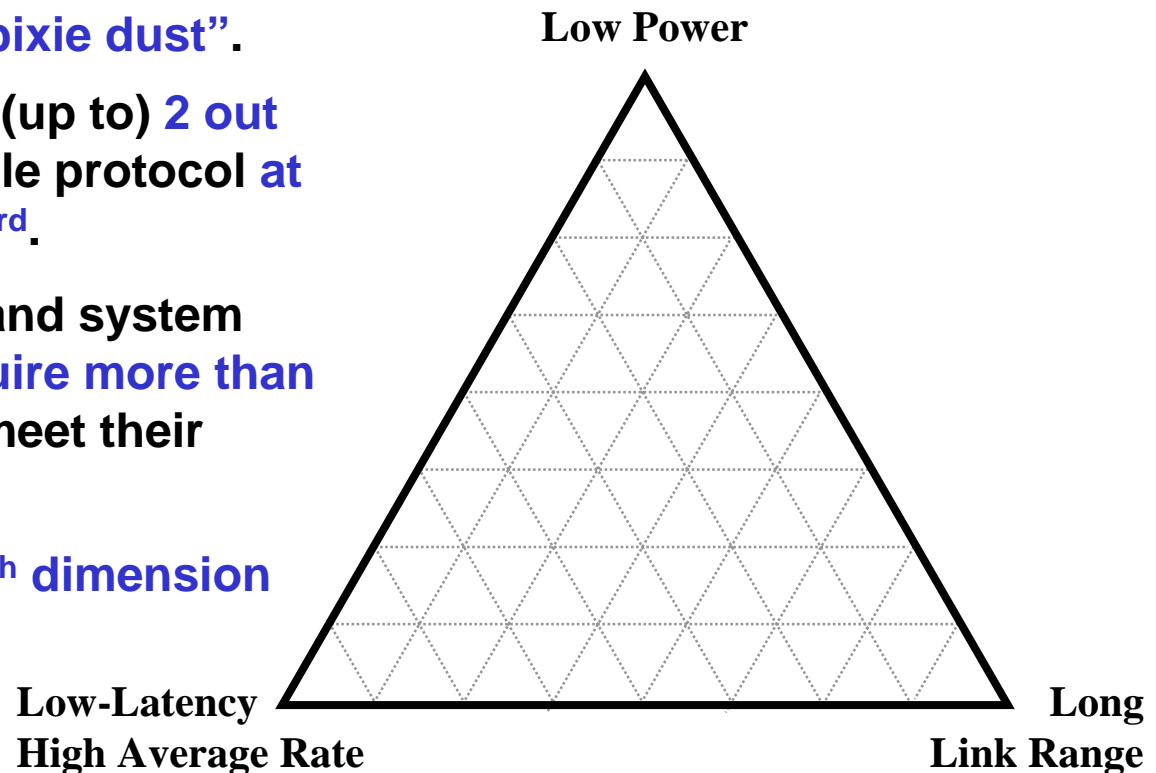
Motorola’s View on Wireless Sensors is Framed by:

- 1. RF Technology Dimensions**
- 2. Business Dimensions**
- 3. Special Factors – Extended Range Scenarios**
- 4. Cellular Data & Emergence of Wireless Ethernet**

Wireless Technology Dimensions

Low Power Operation - High Data Rate, Low Latency - Long Range

- There is no “universal business adapter” or “magic pixie dust”.
- We can optimize for (up to) 2 out of 3 factors in a single protocol at the expense of the 3rd.
- Solution designers and system integrators may require more than one RF protocol to meet their needs.
- Cost is the critical 4th dimension



Business Dimensions

Cost

- RFIC's are the enabler.
- ASIC development is very expensive.
- Cost must be priced into projected unit volumes.
- "Sensors" is not one Market, but an aggregation of many niches.

Interoperability

- An independent interoperability testing & certification organization that promotes a standard (e.g. Wi-Fi™) has proven to be invaluable.

Commercialization, Time to Market

- Production of qualified, standards-compliant IC's lag final changes in the definition by ~12 months.
- Modules follow 3-6 months later & integrated systems after that.
- Wireless Sensor Networks are suddenly becoming fashionable.

Special Factor - Extended Range

Sensors Magazine User Survey:

0-10 m	10-10 ² m	10 ² -10 ³ m	>10 ³ m	(of 27 responses)
32%	41%	0%*	27%	

subcommittee recommendation, ≤1000 m

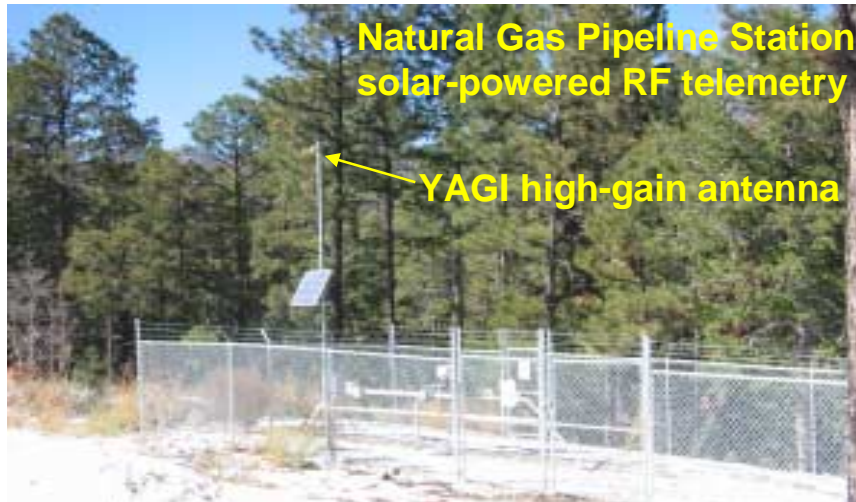
*** An unusual distribution!**

- Is the survey sample lacking in size/diversity? Or....
- Does it capture a need not perfectly expressed by the survey?
- It is reminiscent of Motorola focus group research on 2-way radio users!

We believe the distribution captures a real need for long range wireless data backhaul from remote sensor clusters.

However, burdening all sensors with cost, power consumption of transceivers required for multi-km range is undesirable.

Extended-Range Scenarios



A cluster of sensors at a remote site. Short-to-Medium range wireless nodes can form a sensor network at the site. Satisfied by fixed site pt-2-pt links.



Backhaul Rate-Range Profile fits Cellular

- Low-rate data-services are in their infancy, but service providers are desperate for new (bit and \$ generating) services to fill their data pipes.
- Bursts of aggregated data (gateway backhaul) make more economic sense for carriers (less impact on channel availability for voice). Packet-data oriented systems currently have an advantage (iDEN™ [Nextel], GPRS).
- Many “phones” are now highly capable application platforms (>100 MIPS DSP, J2ME™). So far, mainly used for games.
- Many 2.5G & 3G handsets support SSL connection to WWW servers. A good platform for thin-client network management tools and potentially even sensor network AP/gateways.

WiBridges & WISP extend Ethernet

- Commercial Products offer 4-40 km fixed pt-2-multipoint, pt-2-pt
 - ex: Cisco350 Wireless Bridge™(802.11b), Motorola Canopy™
 - Standard RJ45 10/100 base-T Ethernet interface.
 - 11 Mb/s more than adequate for remote sensor clusters.
- Plug-n-Play connection to Enterprise IT networks using DHCP.
Wireless portion of Ethernet network is transparent.
- Can operate in remote sites on modest solar power.
- Can be built from commodity chip sets (price dropping rapidly).

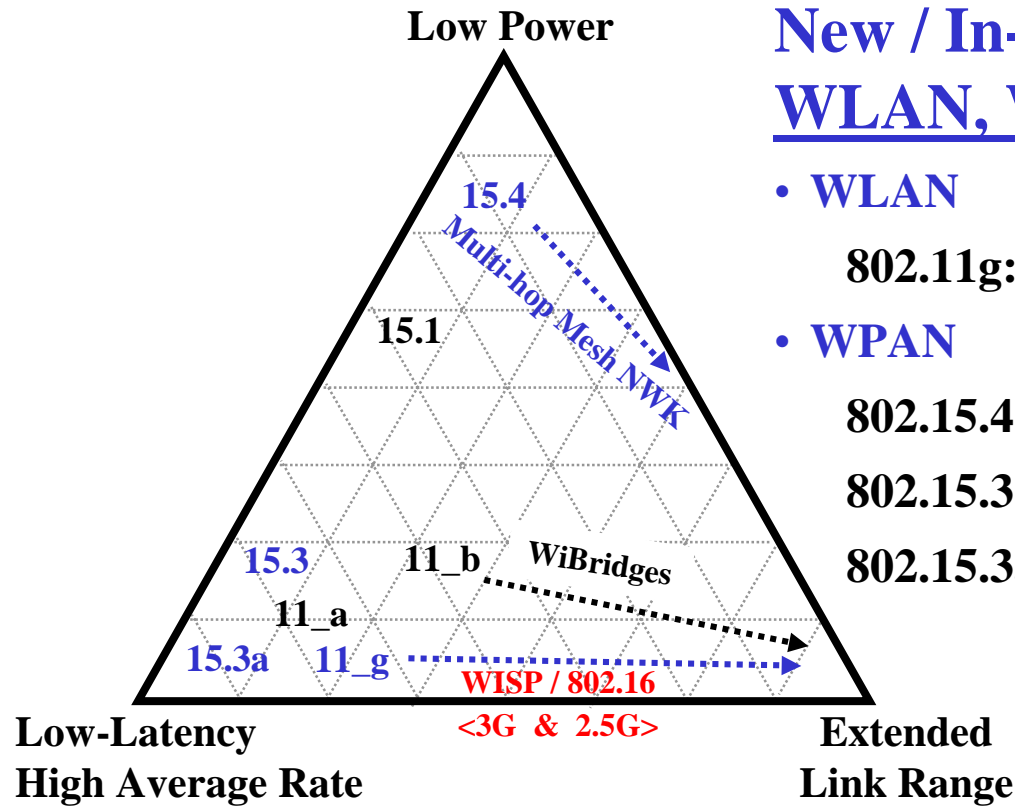
So, how do we use this to our advantage.....?

Our Proposal:

- **Use the “lightest” data framework possible, 1451.0**
(Low rate, battery operated systems are the lowest common denominator, and “every bit transceived is another bit closer to battery death”.)
- **Use IEEE 802.11 & 802.15 Standards in Sensor Nodes.**
- **Make sure Ethernet is part of the wire-line mix.**
- **Part of the Ethernet can be wireless.**
- **Also allow Cellular backhaul via wireless-WWW.**

Wireless Technology Dimensions Map

With the addition of 802.15.4, the IEEE 802.15.x & 802.11x family of WLAN/WPAN standards now provides a solution for all dimensions of the wireless envelope.



New / In-Progress IEEE WLAN, WPAN Standards

- **WLAN**
 - 802.11g: pre-approval products already here!
- **WPAN**
 - 802.15.4: submitted for RevComm approval
 - 802.15.3: est. approval in June
 - 802.15.3a: now reviewing UWB proposals

802 Standards - Applications Focus

802.11b: **Wireless Ethernet**

Adequate for highly-compressed video. Non-isochronous MAC requires buffering, network congestion interrupts. Rapidly increasing adoption by MIS/IT staffs including use in factories & even hospitals. Very long range pt-2-pt links (Wi-Bridges) using outdoor high-gain antennas.

802.11a: **Wireless Ethernet**

Up to 5x rate @ 5.2/5.7 GHz, typically shorter range in practice.

802.11g: **Wireless Ethernet.**

11b vendors competing with 11a data rate at 2.4 GHz.

802.15.1: **Short Range Streaming Data & Voice**

Isochronous support for a few of devices. PC peripherals & headsets.

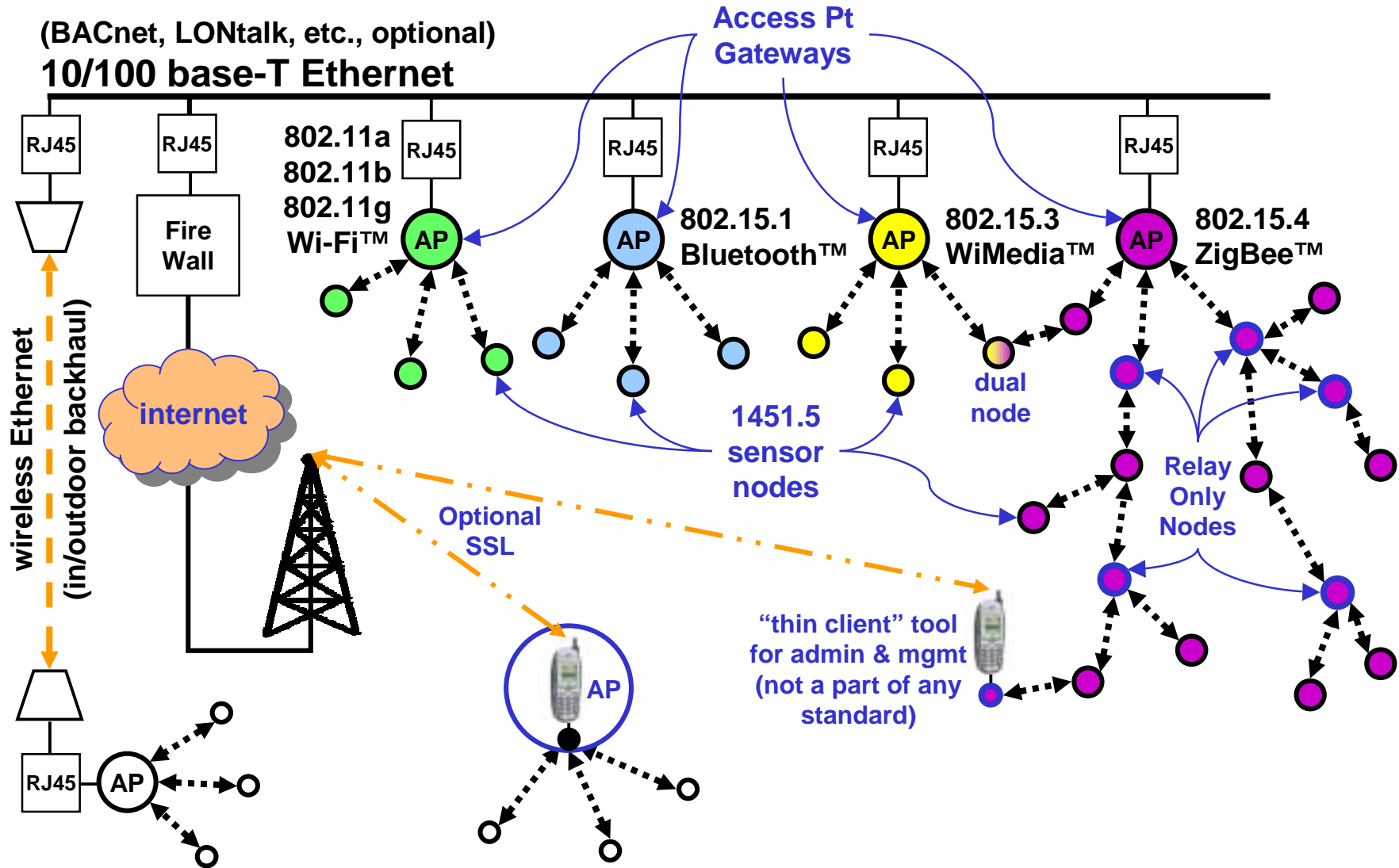
802.15.3: **Streaming Multimedia.**

802.15,3a: **Task group developing alt. UWB PHY, 100-480 Mbps @ 3.1-10.6 GHz**

802.15.4: **Sensor Networks, Home/Industrial Automation, Toys.**

Low Duty Cycle, Long Battery Life, Highly Scalable Networks
Consumer electronics, multiple HDTV channels, plus ISP

Proposed High-Level Architecture



What is Standardized

1. 10/100 Base-T Ethernet (RJ-45)

- shall be the primary wired network interface. Support for other wired networks (including BACnet, LONtalk, etc.) is encouraged, but optional.

2. 1451.0 shall be used for Service Discovery & Payload Data formats.

3. RF Protocols shall be IEEE 802.11x, 802.15.x Standards

- Established Industry Alliances (WiFi, Bluetooth, WiMedia, ZigBee) certify conformance to their respective standards, so 1451.5 does not have to do so.

4. Wireless AP/gateways provide bridging & 1451.x compatibility

- From the wired network, each wireless sensor appears to be an NCAP.
- AP's provide any bridging services to connect nodes on different networks regardless of physical location or wireless protocol, such as:
 - a) Same wireless protocol on physically separated networks
 - b) Same wireless on co-located networks that are logically separated (different systems assigned to different channels, for instance)
 - c) Different wireless (a 802.15.4 door sensor triggers a wired, 802.11x or 802.15.3 video security system).
 - d) Sensors supporting multiple RF protocols may exist as unique devices on each network (video camera communicates directly with door sensor) but do not provide bridging (message transfer between networks).

What is NOT Standardized

1. **Antennas (type, size, diversity), Batteries and Housings**
 - Antenna designs are far too dependent on RF frequency band & application-specific packaging to be standardized.
 - Batteries & Housings likewise are entirely application dependent.
 - All offer opportunities for product differentiation.
2. **Sensor interface to wireless node** (sensor+wireless node will typically be a “black box” to end users.) A product differentiator.
3. **Radio interface to microprocessor** (intelligence) in wireless sensor or gateway processor.
4. Existence of, or interface to, **computation-enhanced nodes**.

Advantages of the Proposal

Flexibility

- **System Integrators & Solution Providers can choose the right tool for each job.**
- **Avoids the “one-size-fits-all, badly” trap of “streaming video to the toaster”.**
- **With 802.15.4, IEEE Standards cover the necessary dimensions for sensors.**

Recognizes Market Realities

- **Multiple markets & suppliers for 802.11x, 802.15.x standards drives lowest cost.**
- **Most sensors won't notice if a portion of Ethernet connection is wireless.**
- **IT organizations taking over, Ethernet is their “standard of standards”.**
- **Turns rapidly proliferating 802.11b into an ally.**

Resource Utilization

- **Leverage Industry Alliances for RF compliance testing & certification.**
WECA™ “WiFi” (802.11), Bluetooth™ (802.15.1),
WiMedia™ (802.15.3) & ZigBee™ (802.15.4).
- **Focus 1451.5 on value-added factors unique to smart sensors.**
Service Discovery: TEDS, Binding methods.
Extensions for stronger security (as needed).

**A detailed look at the
IEEE 802.15 & 802.11
families of Standards**

802.15.4 MAC

Superframe structure with Guaranteed Time Slots

Coordination

- Beacon mode uses slotted CSMA/CA, Guaranteed Time Slots assignable in CFP.
- **No support for isochronous data.**
- Non-Beacon mode uses un-slotted CSMA/CA. Supports purely event-driven traffic. Rx-ACK avoids “blink repetition” of 1way.

Network Support

- 64-bit unique address in each node.
- Up to 254 nodes per Coordinator (Master-Slave).
- Optional short (16-bit) logical addresses.
- Up to 65,534 nodes peer-to-peer (mesh).

Optional Frame Acknowledgement

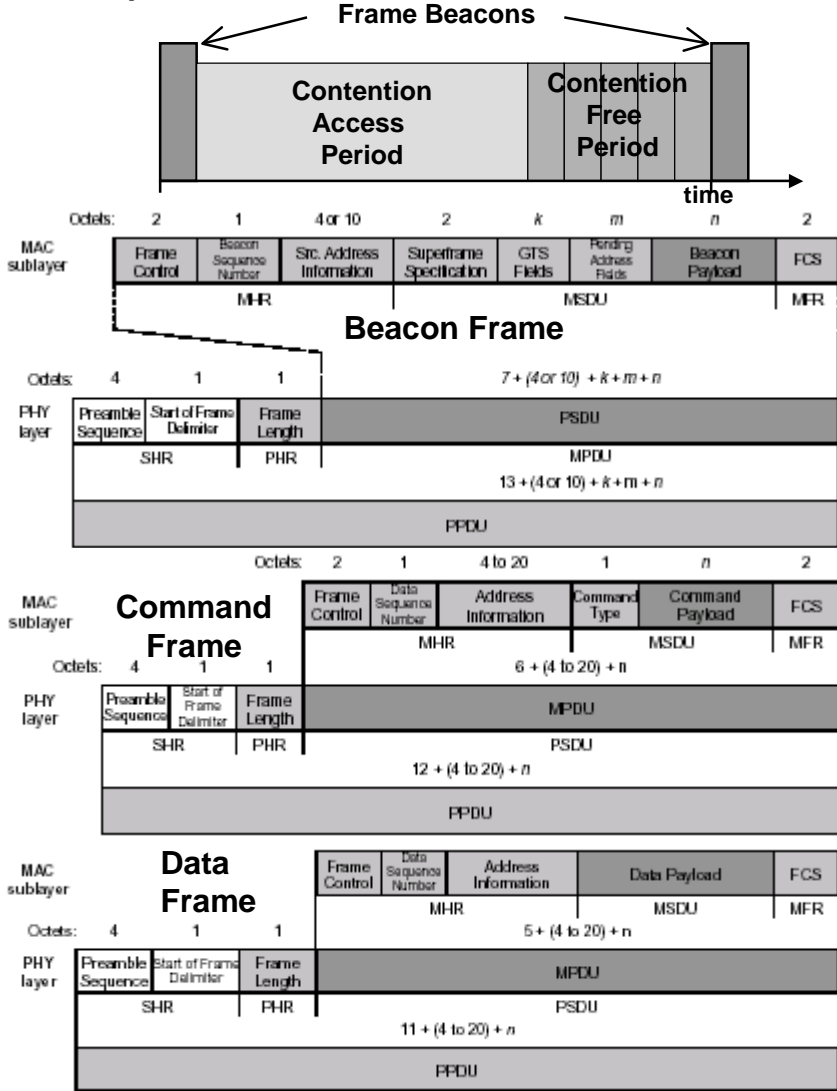
- Lack of requested ACK triggers re-try (#attempts to failure at sender’s discretion).

Data Verification, Security

- 16 bit CRC
- 128 AES encryption & authentication (optional)

Fragmentation/De-fragmentation

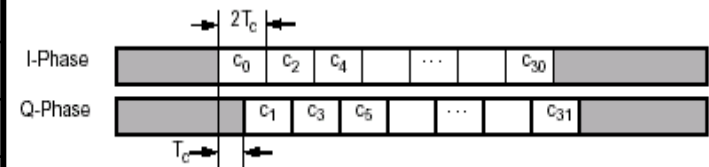
- Not specified (left for upper layers)
- Max Packet Size = 128 bytes (1-103 min payload)



802.15.4 PHY

DSSS Specification	868 / 915 MHz	2450 MHz
Frequency (MHz)	868.0-868.6 / 902-928	2403-2480
# Channels	1 / 10	16
Symbol Rate (Ksym/s)	20 / 40	62.5
PN Sequence Length	15	32
Chip Rate (Kchips/s)	300 / 600	2000
Symbols	Binary	16-ary orthogonal
Data Rate (kb/s)	20 / 40	250
Carrier Modulation	BPSK	O-QPSK
Pulse Shaping	Raised COS (r.f.=1)	1/2 SIN
Min. RX Sensitivity (dBm)	-92	-85
Min. Adj. Chan. Rej. (db)	n.a. / 0 (2 MHz)	0 (5 MHz)
Min. Alt. Chan. Rej. (db)	n.a. / 30 (4 MHz)	30 (10 MHz)
Max. Freq. Tol. (± ppm)	40	40
RX Synch. Preamble	1600 / 800 μs (32 bits)	128 μs (32 bits)
RX-TX, TX-RX turnaround	600 / 300 μs (12 sym)	192 μs (12 sym)
Min. TX Power (mW)	0.5	0.5
Max TX Power (mW)	Regulatory Limits	Regulatory Limits

2450 MHz DSSS detail



Chip Rate = $1/T_c$

Symbols are mapped to chips by 1 of 16 nearly-orthogonal PN sequences generated by cyclic shifts & conjugations of a single base PN code. (Single base code keeps RX design small, low current.)

1 of 16 sequences = 4 bits/symbol

Constant-Envelope modulation allows low cost, efficient PA (both bands).

802.15.4 Security Support

Identifier	Access Security Suite Name	Security Services			freshness (optional)
		Data control	Frame encryption	Sequential integrity	
0x00	None				
0x01	AES-CTR	X	X		X
0x02	AES-CCM-128	X	X	X	X
0x03	AES-CCM-64	X	X	X	X
0x04	AES-CCM-32	X	X	X	X
0x05	AES-CBC-MAC-128	X		X	
0x06	AES-CBC-MAC-64	X		X	
0x07	AES-CBC-MAC-32	X		X	

If any security is implemented, AES-CCM-64 is mandatory, other modes are optional.

ZigBee™ Alliance

www.zigbee.org

Promoters:

Honeywell, Invensys, Mitsubishi, Motorola, Philips

Participants:

Adcon RF Technology BV, AlfaPlus Semiconductor, Inc., AMI Semiconductor, Inc., Analog Devices, Ardesta, Atmel Corporation, Cambridge Consultants, Certicom Corporation, Chipcon, CompXs, CSEM SA, Danfoss A/S, Eaton Corporation, Eazix, Inc., Ember Corporation, ETS Dr. Genz (U.S.A.), Inc., Figure 8 Wireless, Inc., France Telecom, Helicomm Inc., Inovonics Wireless Corporation, Intel Corporation, Integration Associates, ITE, Inc., KETI (Korea Electronics Technology Institute), Leviton Mfg. Company, Inc., Microchip Technology, Micro Linear, Millennial Net, Inc., Nanotron Technologies GMBH, National Technical Systems, NTRU Cryptosystems, Inc., OKI Electric Industry Co. Ltd., Omron Advanced Systems, Inc., RF Micro Devices, Robert Bosch Corporation, Uniband Electronic Corporation, Xanboo Inc., Xemics, Zensys A/S, ZMD AG

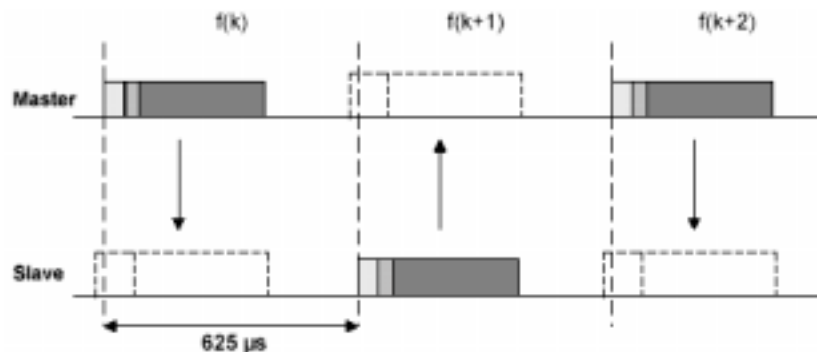
Status:

802.15.4 approval by IEEE-SA Review Committee board anticipated on 7 May 2003.
Draft available from IEEE by 27 March, Product#:UE5916 ISBN:0-7381-3660-3
Feb '03: 7 Multi-hop/Mesh Network Proposals down-selected to 1 (merged) proposal.
Security Group Discussion is on-going.

Proposed Network Schedule:

Preliminary Specification: June 2003, Final Draft: November 2003, Board Approval ~ March '04

802.15.1 MAC



Time Division Duplex

- Master and Slave alternatively transmit

Master-Slave Mode

- 48-bit unique address in each node
- Up to 7 active slaves per Piconet (up to 247 “parked”)

Error Correction

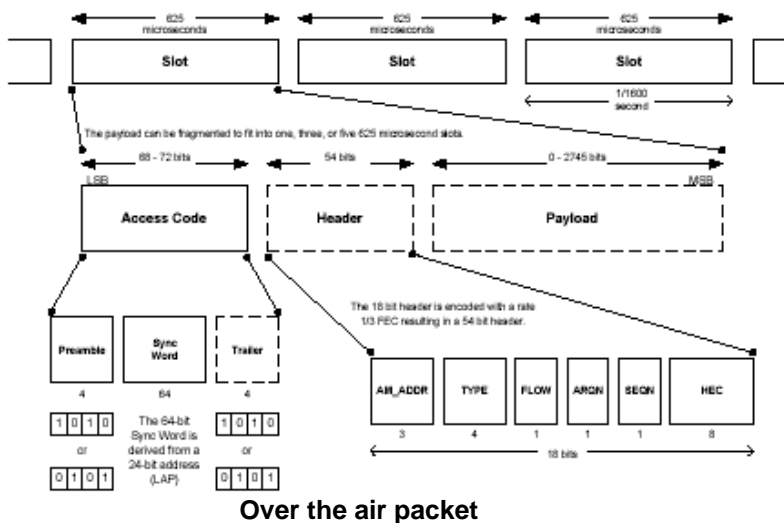
- 1/3 FEC
- 2/3 FEC
- ACQ scheme for data

Data Verification

- 16 bit CRC protection

Security

- Authentication
 - Challenge-response scheme
- Encryption on payload
 - Re-synchronized for every payload
- Up to 128-bit, Streaming Cipher
 - Dependent upon where in the world it is used
- Trusted device list



Thanks to Jens Hult, Oceana Sensor for compiling information on this slide.

802.15.1 PHY

FHSS Specification	2450 MHz
Frequency (MHz)	2402-2480
# Channels	79
Symbol Rate (Ksym/s)	1000
Data Rate (kb/s)	1000
Carrier Modulation	GFSK
Bandwidth Time (BT)	0.5
Modulation Index	0.32
Hops/second	1600
Min. RX Sensitivity (dBm) 0.1% BER	-70
Min. Adj. Chan. Rej. (dB)	0
Min Alt. Chan. Rej. (dB)	30
Max. Freq. Tol. (\pm ppm)	40
Max. RX RF Input (dBm)	-20
RX Sync. Preamble	4 + 64 bits
Min. TX Power (dBm)	-6

Thanks to Jens Hult, Oceana Sensor for compiling information on this slide.

Bluetooth™ Special Interest Group

www.bluetooth.com

Promoters:

Ericsson, Nokia, Intel, Motorola, Philips, Toshiba, 3Com, Agere, Microsoft

Participants:

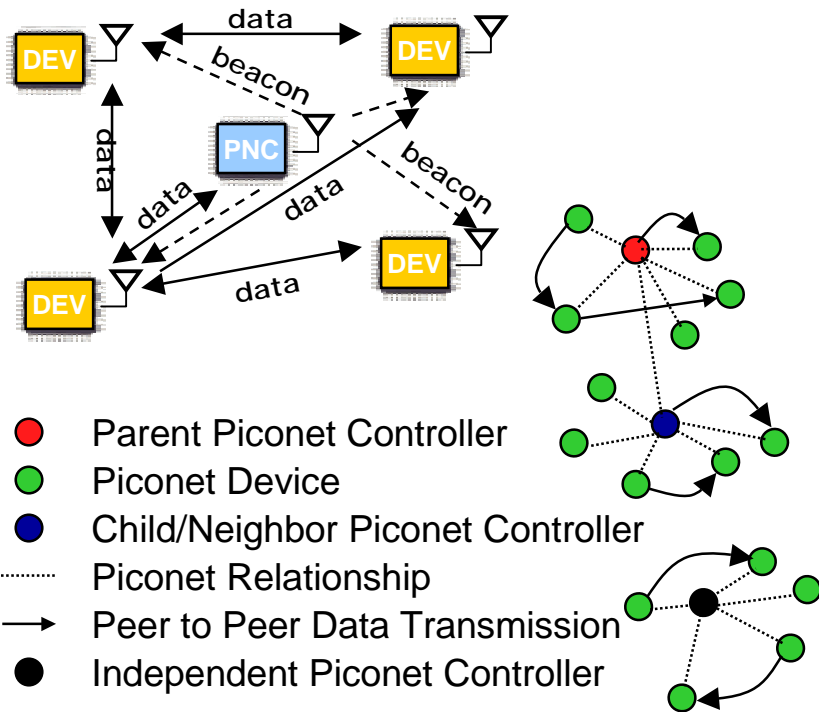
ABB, Agilent Technologies, Blue2Medical Technologies, Bluegiga Technologies Oy, BMW Group, Cambridge Consultants Limited, Cambridge Silicon Radio, Cirrus Logic, Code Blue Communications, connectBlue AB, DaimlerChrysler AG, Ford Motor Company, F-Secure Corporation, General Motors, Honeywell, Infineon Technologies AG, Internet Control Solutions, Kvaser, National Semiconductor, Oceana Sensor Technologies Inc., Palm Inc., Parker Hannifin Corporation, Qualcomm Inc., Roving Networks Inc., Siemens AG, SiGe Semiconductor Inc., Sensoria Corporation, Silicon Wave Inc., SKF Nova AB, STMicroelectronics, Symbol Technologies Inc., Techkor Instrumentation, Texas Instruments Inc., Volkswagen AG, Wilcoxon Research, Zeevo Inc., and many more

Status:

Bluetooth™ Specification version 1.1 approved February 22, 2001
IEEE 802.15.1 approved April 15, 2002

Thanks to Jens Hult, Oceana Sensor for information on this slide.

802.15.3 MAC



Coordination

- Beacon, Command, Data, Ack frame types
MCTA & CTA in Contention-Free Period
CSMA/CA in optional CAP
- Piconet: start, handover, create dependent, end.
- Selects channels according to 802.11b presence
- 0.512 ms (short), 65.535 ms (long) superframes
- Isochronous Stream management designed for wireless video, multi-media.

Power management

- Controller TX Power Set & Dev Request change.
- Device or Piconet Synched & Asynch Sleep.

Fragmentation/De-fragmentation

- Fragmentation Control in MAC header
- Max (worst case) Packet Size = 2044 bytes

Security

- 64 bit IEEE unique address
- 32 bit CRC protection
- Devs authenticate with Controller, other Devs
- Command & payload frame protection
- AES-128 encryption

Superframe #m-1		Superframe #m				Superframe #m+1	
Beacon #m	Contention Access Period	Contention Free Period					
		MCTA 1	MCTA 2	CTA 1	CTA 2	...	CTA n-1

802.15.3 PHY

Specification	2.4 GHz High Density / 802.11b Co-existence
Frequency (GHz)	2.40 – 2.4835
# Channels	4 / 3
Symbol Rate (Msym/s)	11
Data Rate (Mb/s)	11, 22, 33, 44, 55
Carrier Modulation	QPSK, DQPSK, 16-QAM, 32-QAM, 64-QAM
Symbol Coding	8-TCM, none, 8-TCM, 8-TCM, 8-TCM
Min. RX Sensitivity (dBm)	-82, -75, -74, -71, -68
Min. Adj. Chan. Rej. (db)	33, 26, 25, 22, 19
Min. Alt. Chan. Rej. (db)	48, 41, 40, 37, 34
Max. Freq. Tol. (\pm ppm)	25
Max. RX RF Input (dBm)	-10
RX Synch. Preamble	0.91 us (10 CAZAC symbols)
RX-TX, TX-RX turnaround	10 us
Min. TX Power (mW)	Not defined

mandatory, optional

WiMedia™ Alliance

www.wimedia.org

Promoters:

Apparent Technologies, Eastman Kodak, Hewlett-Packard, Motorola, Philips, Samsung Electronics, Sharp Laboratories, STMicroelectronics, Time Domain, XtremeSpectrum

Contributors:

Infineon Technologies, LG Electronics, Open Interface North America, TRDA, Wisair

Status:

- IEEE 802.15.3 Committee Chairman projects a final Sponsor Recirculation Ballot in early April, and draft standard ready for final approval in June.
- 802.15.3a Task Group is now reviewing UWB proposals.

802.11b

Specification	DSSS basic / enhanced	FHSS
Frequency (GHz)	2.4-2.497	
# Channels	14 (overlapping) F.C.C. allows #1-11	
Symbol Rate (Msym/s)	1 / 2 / 5.5, 11	
PN Sequence Length	11 (Barker Code)	
Chip Rate (Mchips/s)	11	
Symbols	Binary	
Data Rate (Mb/s)	11 / 22	
Carrier Modulation	DBPSK / DQPSK / CCK	
Pulse Shaping	Gaussian	
Min. RX Sensitivity (dBm)	-80 dBm	
Min. Adj. Chan. Rej. (db)	>35 dB (30 MHz)	
Max. Freq. Tol. (\pm ppm)	25	
RX Synch. Preamble	144 us	
RX-TX, TX-RX turnaround	5 us, 10 us	
Min. TX Power (mW)	1	

802.11a PHY

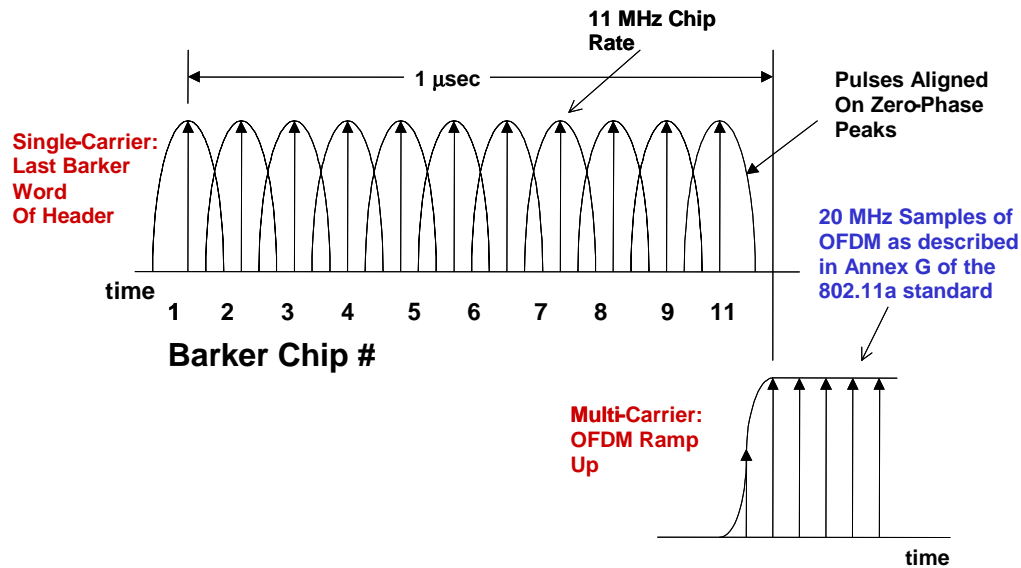
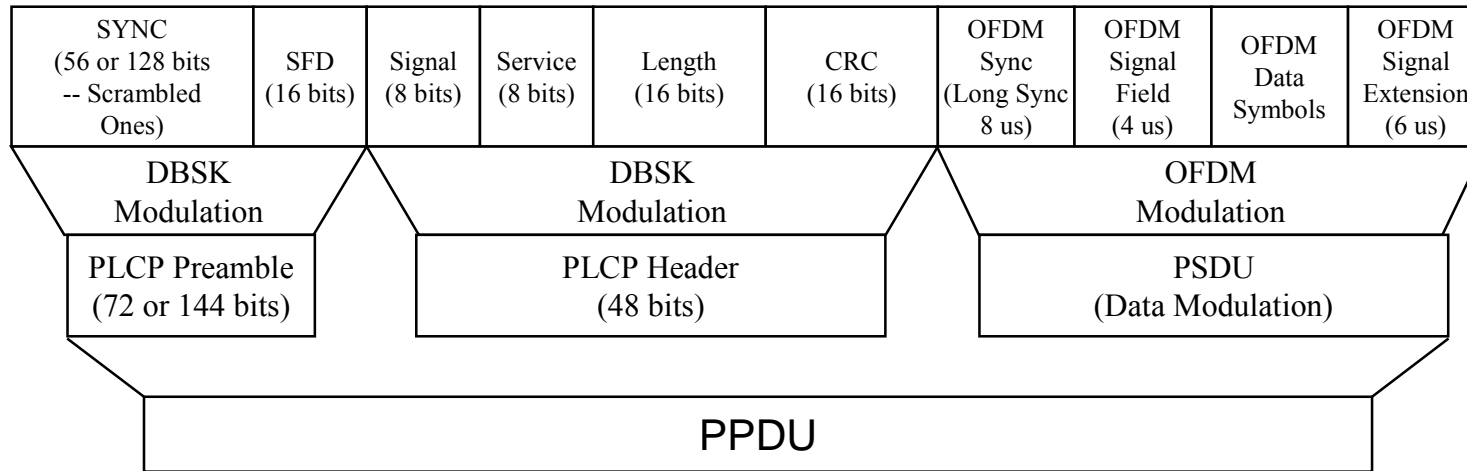
Specification	OFDM
Frequency (GHz)	5.15-5.25 / 5.25-5.35 / 5.725-5.825
# Channels	12 in US (F.C.C.)
Carrier Modulation	BPSK, QPSK, 16-QAM, 64-QAM
Number of Subcarriers	52 @ 0.3125 MHz {=20 MHz/64} spacing
Data Rate (Mb/s)	6, 9, 12, 18, 24, 36, 48, 54 (mandatory, optional)
FEC Coding Rates	$\frac{1}{2}$, $\frac{3}{4}$, $\frac{1}{2}$, $\frac{3}{4}$, $\frac{1}{2}$, $\frac{3}{4}$, $\frac{2}{3}$, $\frac{3}{4}$
Coded Bits per Subcarrier	1, 1, 2, 2, 4, 4, 6, 6
Data Bits per Symbol	24, 36, 48, 72, 96, 144, 192, 216
Min. RX Sensitivity (dBm)	-82, -81, -79, -77, -74, -70, -66, -65
Min. Adj. Chan. Rej. (db)	16, 15, 13, 11, 8, 4, 0, -1
Min. Alt. Chan. Rej. (db)	32, 31, 29, 27, 24, 20, 16, 15
Max. Freq. Tol. (\pm ppm)	20
RX Synch. Preamble (μ s)	20
RX-TX turnaround (μ s)	2
Min. TX Power (mW)	not specified
Max. TX Power (mW)	40 / 200 / 800 (with up to +6 dBi antenna gain)

802.11g PHY

Specification	DBPSK / OFDM / PBCC
Frequency (GHz)	2.403 - 2.803
# Channels	14 overlapping (FCC allows #1-11)
Carrier Modulation	PBCC & OFDM
Data Rate (Mb/s)	1, 2, 5.5, 6, 9, 11, 12, 18, 22, 24, 33, 36, 48, 54
Min. RX Sensitivity (dBm)	6, 9, 12, 18, 24, 36, 48, 54 / 22, 33 -82, -81, -79, -77, -74, -70, -66, -65 / -76, -74
Min. Adj. Chan. Rej. (db)	16, 15, 13, 11, 8, 4, 0, -1 / 35, 35
Max. Freq. Tol. (\pm ppm)	25
RX Synch. Preamble (μ s)	144
RX-TX, TX-RX turnaround (μ s)	5
Max. RX Input (dBm)	-20

**OFDM mode appears to be essentially a translation of .11a modulation to 2.4 GHz.
PBCC mode appears to be essentially an increased rate .11b (CCK) mode.
Initial Synchs & Preambles are as in 11b to provide backward compatibility.**

802.11g DSSS-OFDM Transition



Wi-Fi Alliance

<http://www.wi-fi.org>

Members:

Too many to list. See the website.

Status:

802.11b: Completed. Commodity products available.

802.11a: Completed. Commercial products available.

802.11g: Draft standard approved by Working Group. Final approval expected in mid-June, publication in late July 2003. Early (compliance risk) products already on the market.

2.4 GHz Coexistence

802.15.2 is Coexistence Task Group

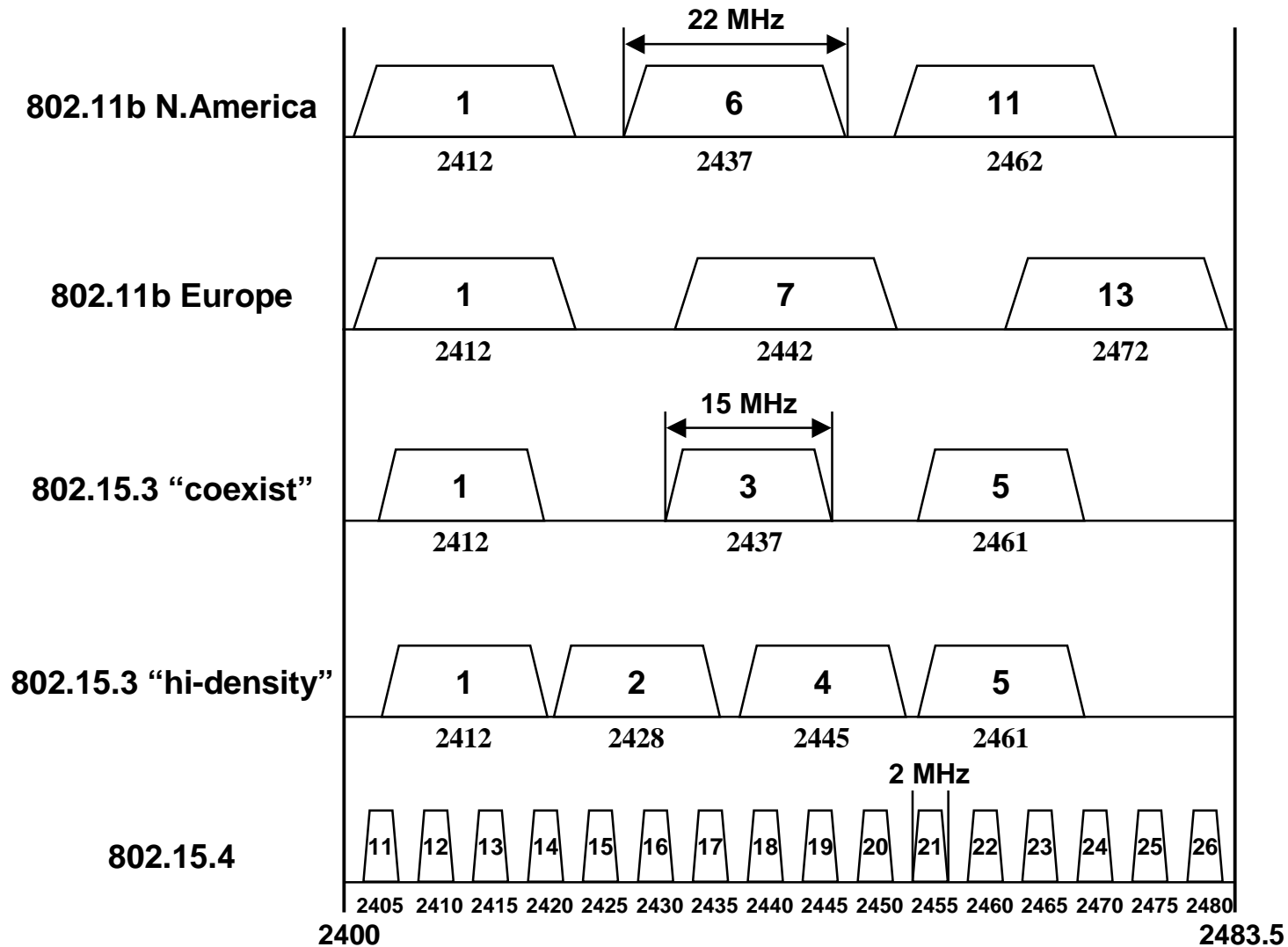
802.15.4

- 0 dBm, 2 MHz DSSS will not impact other systems @ 2.4 GHz.
- DSSS advantageous for multiple access
- Bluetooth presence on 15.4 channel is brief (0.625 ms), low%.
- 802.11b,g are bursty in nature. “Many lulls in the storm”.
- Short Packets, CSMA/CA, ACK ensure reliable operation.
- 15.4 Apps are characteristically not latency-critical.
- 15.4 AP/gateways, if using 802.11b,g wireless Ethernet backhaul, will be able to manage their transmissions appropriately.

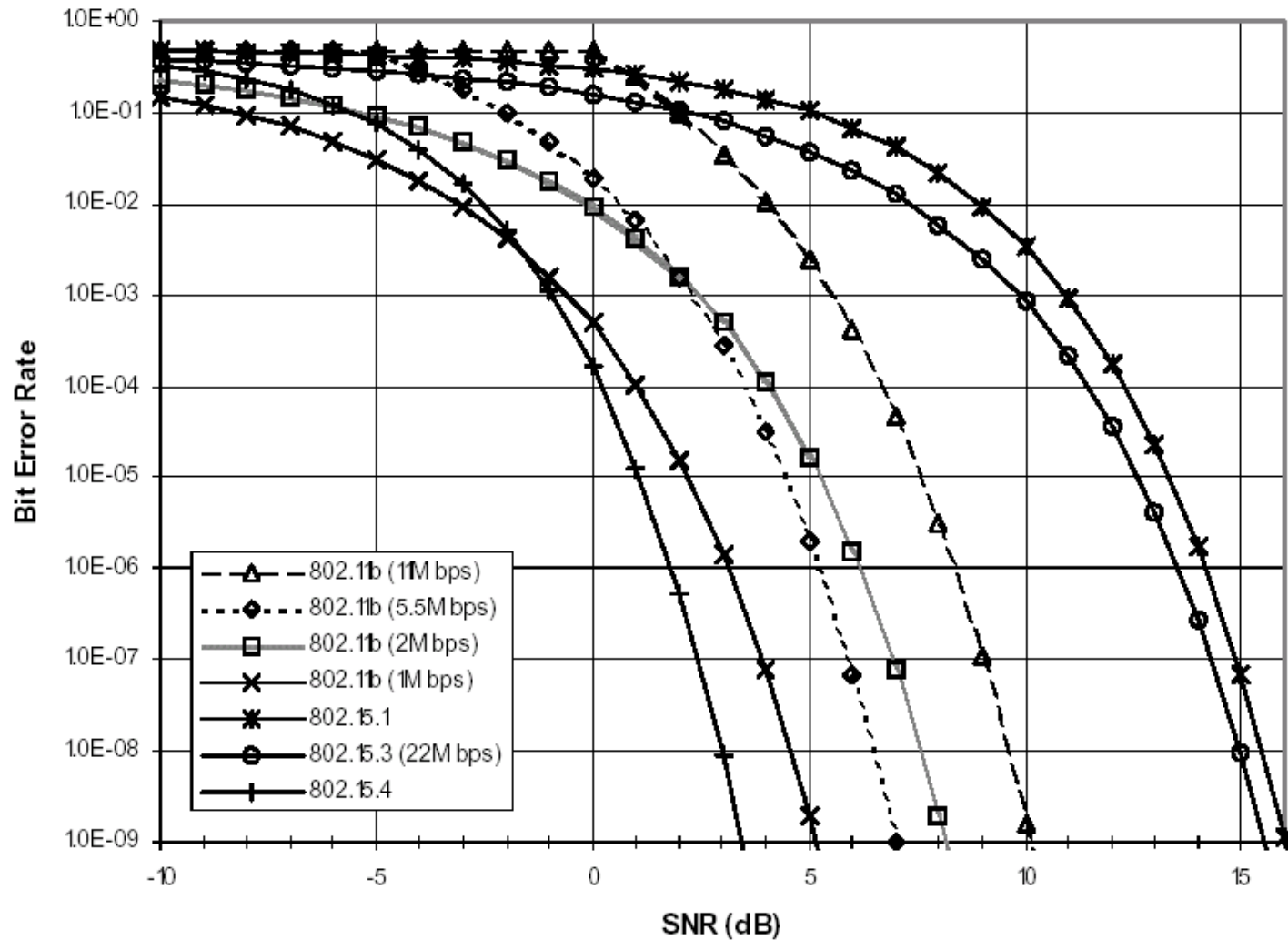
802.15.3

- Dynamic Channel allocations designed for 802.11b coexistence.

2.4 GHz ISM Band Channel Alignment



802.11b, 802.15.x BER Comparison



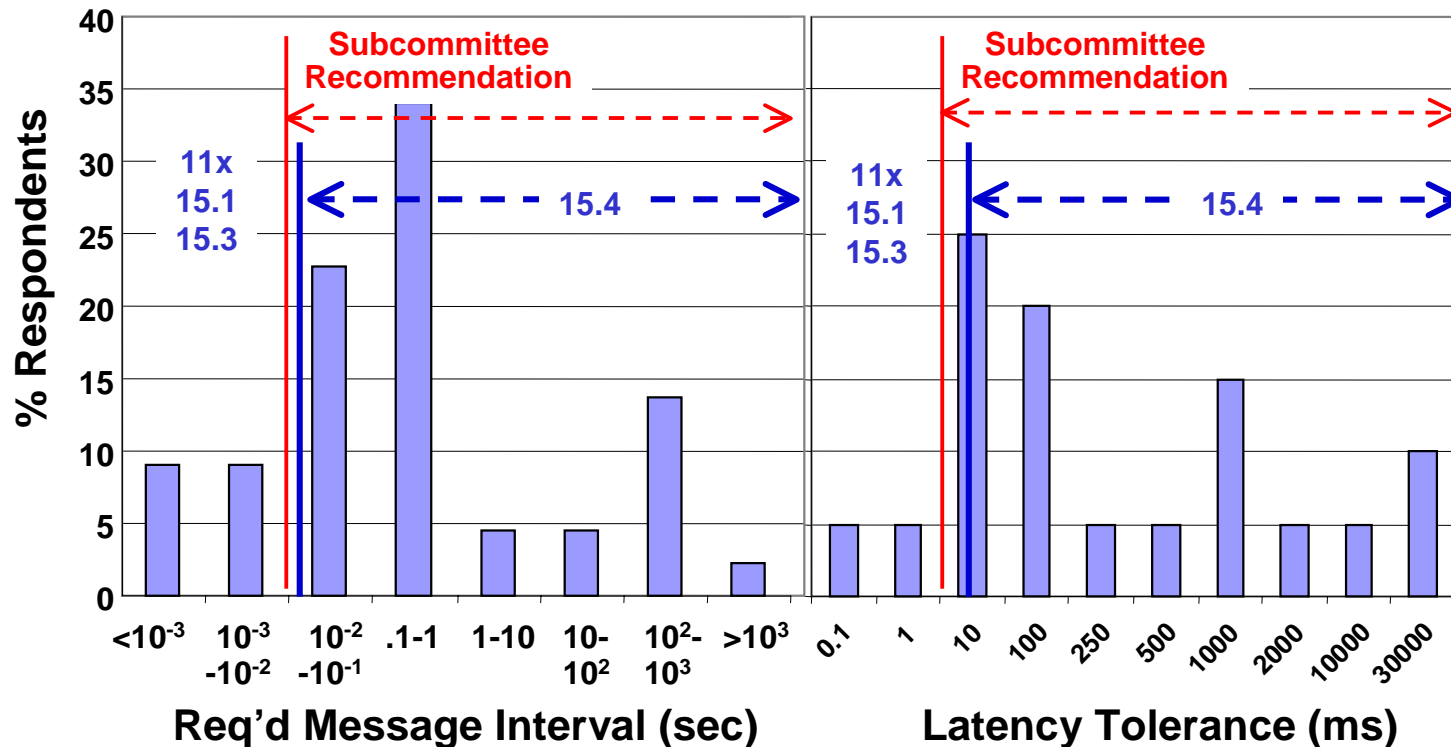
Source: d18_P802.15.4 Annex E: Coexistence with other IEEE standards and proposed standards.

Proposal Comparison to Requirements

How does this proposal compare against the User Needs expressed in our Surveys & Subcommittee Recommendations?

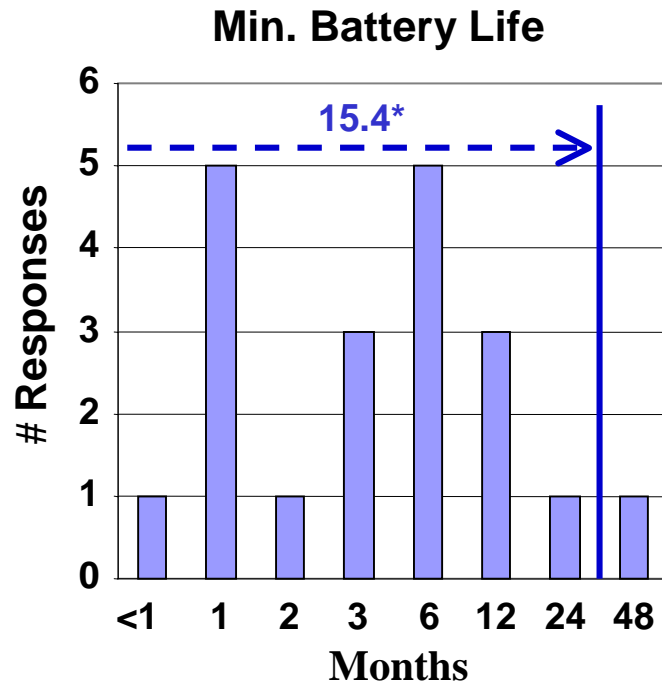
ALL criteria are fully met!

Proposal Comparison to Survey, Criteria

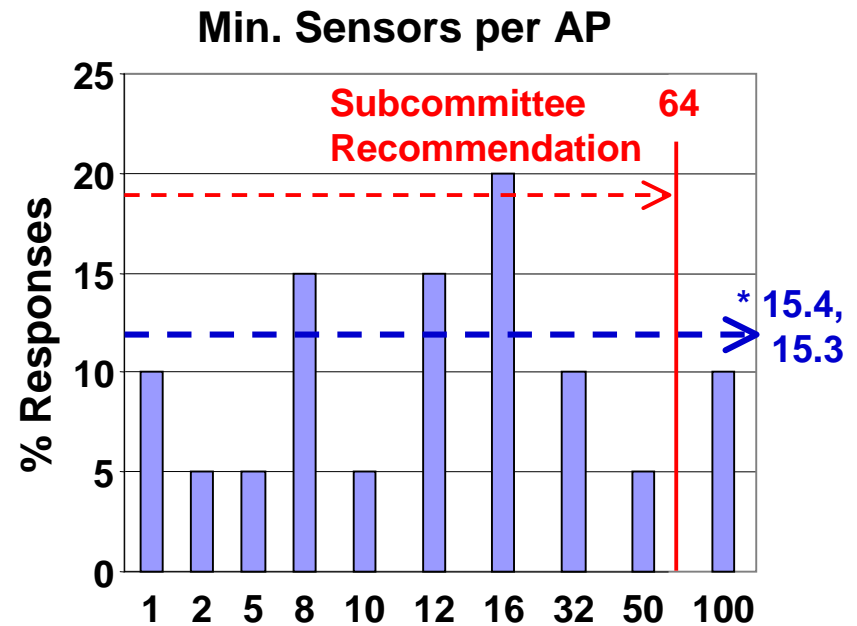


- Survey resolution is low due to the huge dynamic range of requirements.
- The 15 ms beacon mode of 15.4 will meet the need of most users in the 10-100 ms range for Message Interval / Latency.

Proposal Comparison to Survey, Criteria

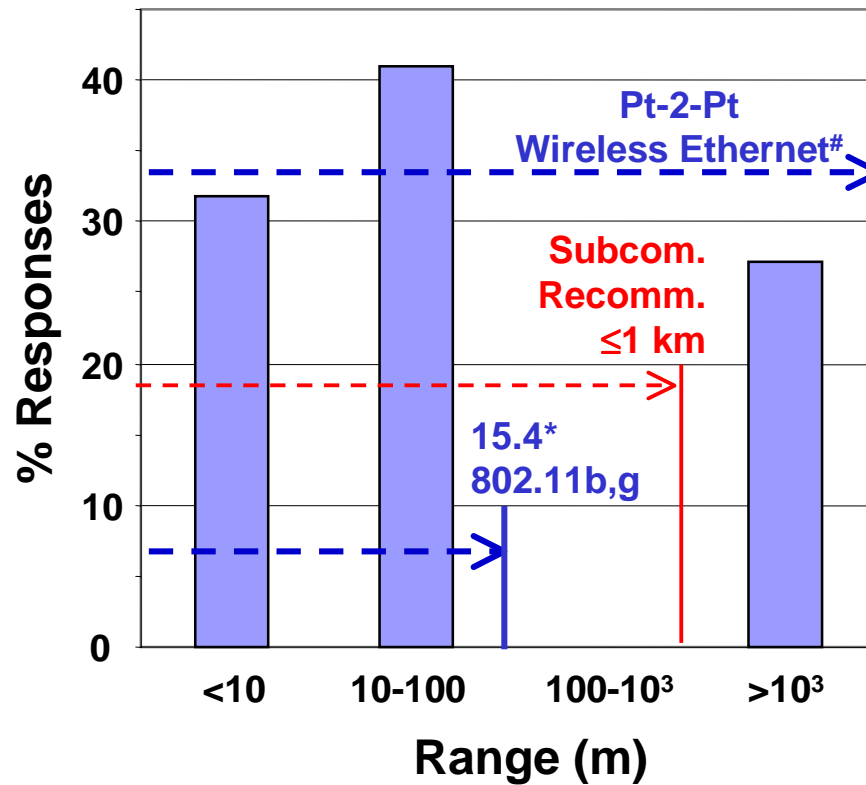


*0.1% duty (Rx,Tx w/ μ C) on 2AA [1500 mA-hr @ >2V], radio & microcontroller only.



*254 nodes per Coordinator in 15.3, 15.4 stars 65,534 nodes/AP in multi-hop ZigBee™ NWK.

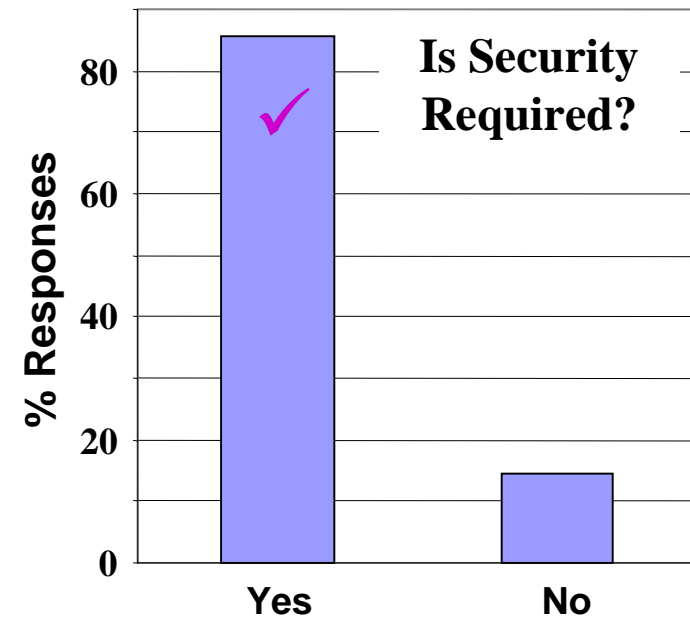
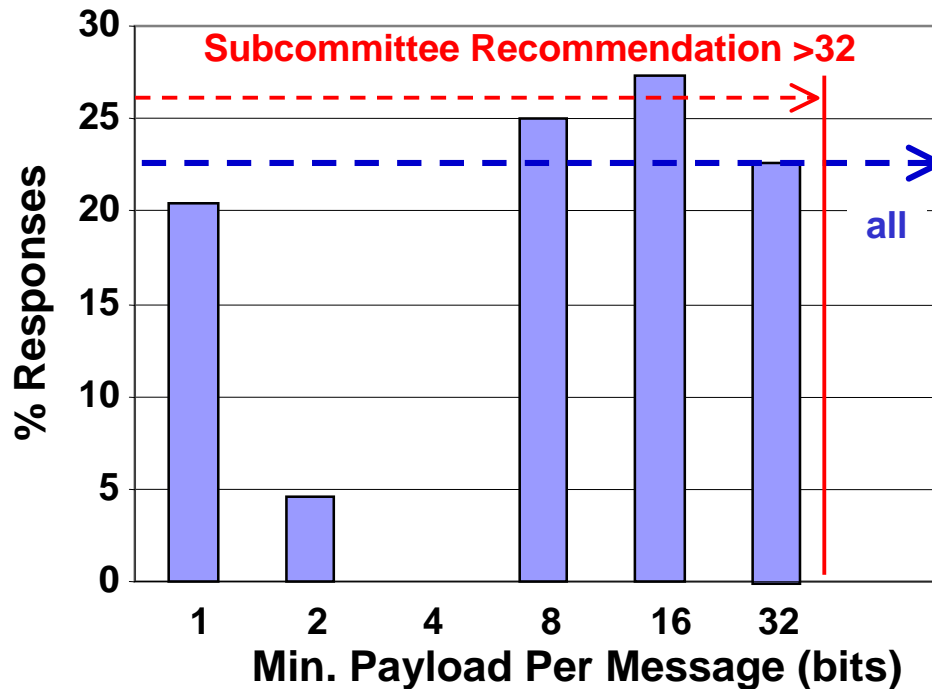
Proposal Comparison to Survey, Criterion



* ZigBee™ multi-hop network will cover 10m-100m range for latency-tolerant applications, or by use of additional PA to increase TX power

Pt-2-Pt Wireless Ethernet and/or Cellular can cover >1 km backhaul from remote sensor clusters.

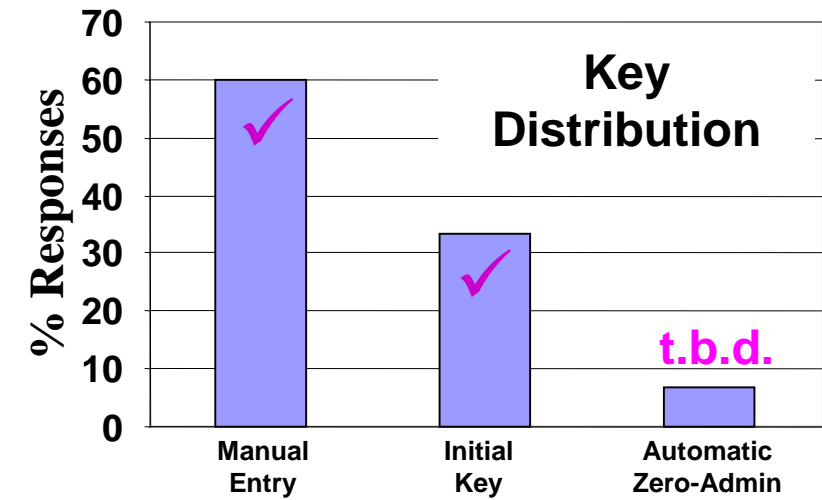
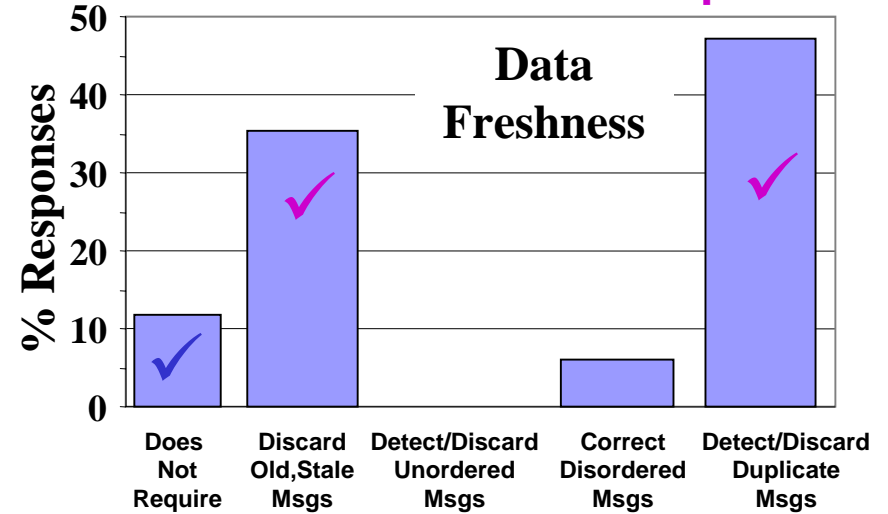
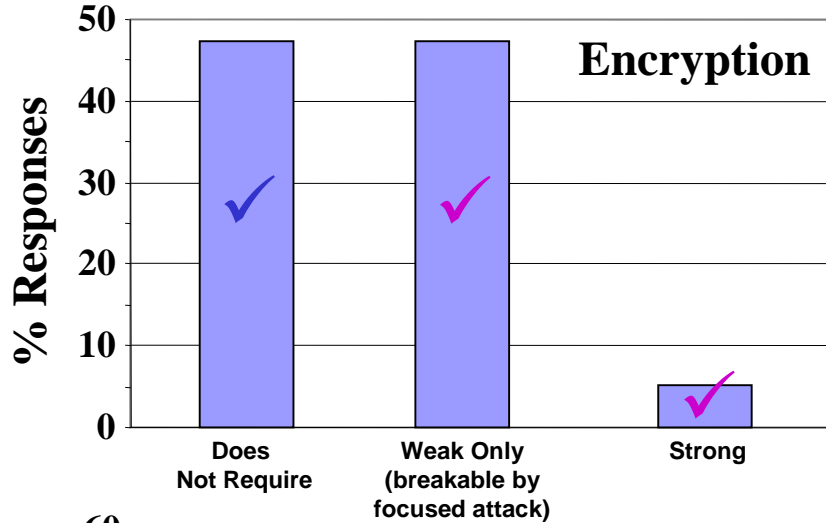
Proposal Comparison to Survey, Criterion



Obviously!

Proposal Comparison to Survey, Criterion 802.15.4

✓ mandatory
✓ optional



Summary

- **No one protocol can cover ALL aspects as well.**
- **By design, 802.15.4 is well-suited for wireless sensing apps.**
Increased link range can be obtained by increasing TX power.
- **Other 802.11 & 802.15 standards already address high rate, low latency, & isochronous QoS (streaming data) needs of:**
Streaming Video (Security)
High Sample-Rate Real-Time Telemetry (engine, vibration monitoring, etc.)
- **Proprietary solutions offer NO SIGNIFICANT ADVANTAGE over a similarly-optimized open standard.**
- **Wireless Ethernet & Cellular provide extended-range backhaul, and the potential for Global connectivity (if you want it).**

General Solution Criteria

Criteria	Ref	Value
Unit Manufacturing Cost (\$) (assuming high volume) radio module BOM [no requirement]	Estimates based on literature values only	802.11a: \$ 802.11b: \$20-25 802.11g: \$ 802.15.1: \$12-15 802.15.3: \$30; 15.3a: \$30 802.15.4: \$5
Installation Cost (\$) per node, amortizing cost of AP installation & frequency planning across all nodes. [no requirement]	Wired = High to Very High	802.11a: medium 802.11b: medium 802.11g: medium 802.15.1: low 802.15.3: low 802.15.4: very low
Time To Market [no requirement]		802.11a: commercial IC's & modules 802.11b: commodity IC's & modules 802.11g: commercial IC's & modules 802.15.1: commodity IC's & modules 802.15.3: by completion of 1451.5 802.15.4: evaluation of 1 st silicon

General Solution Criteria

Criteria	Ref	Value
Regulatory Impact [no requirement]	IEEE Standards documents	802.11a: none 802.11b: none 802.11g: none 802.15.1: none 802.15.3: none; 15.3a: FCC UWB emission limits 802.15.4: none
Size and Form Factor [no requirement]		802.11a: PCMCIA + external power 802.11b: PCMCIA + power adapter or lg. battery 802.11g: PCMCIA + external power 802.15.1: nearly battery-limited except coin-cells 802.15.3: limited by camera for streaming video 802.15.4: battery-limited except coin-cells
Intrinsic Safety [as an option]		implementation & industrial design dependent All standards capable of operation at ≤ 100 mW EIRP

General Solution Criteria

Criteria	Ref	Value
Maturity of Solution (i.e. demonstration of technology) [no requirement]		802.11a: commercially available, multiple vendors 802.11b: mature commodity 802.11g: commercially available 802.15.1: mature commodity 802.15.3: in preparation, commercialization is tbd 802.15.4: new standard, commercial in 2004
Interoperability (with IEEE 1451 family)		YES, by gateway services
Scalability [no requirement]		802.11a: by adding AP/Gateways 802.11b: by adding AP/Gateways 802.11g: by adding AP/Gateways 802.15.1: 7 active/AP, by adding AP/Gateways 802.15.3: 254/PNC; by adding AP/Gateways 802.15.4: 254-65,500/PAN_Coord.+interPAN NWK
Dynamic Power Management [no requirement]	IEEE Std Docs	802.11a: not specified 802.11b: EIRP>20dBm, shall cut back to <20 dBm. 802.11g: not specified 802.15.1: Class 1 ($\leq +20$ dBm) shall cut back to $\leq +4$ dBm 802.15.3: Settable in CAP, Beacons; adjustable in CTA 802.15.4: TX cutback capability suggested

General Solution Criteria

Criteria	Ref	Value
Power Consumption [no requirement]	Cisco Aironet 350 Client Linksys WCP11 ver.3.0 TI - BRF6100 (preliminary) XSI-Trinity Motorola - MC13192 (preliminary)	802.11a: 802.11b: 450mA TX, 270mA RX, 15mA SLEEP (5V) 275mA TX, 225mA RX, 20mA Sleep (3.3, 5.0 V) 802.11g: 802.15.1: 75mW active; 60uW sleep 15.3a: 300mW active (~75mW idle) 802.15.4: 60mW active; 5, 60, 2000µW sleep
Sensor Data Throughput		see Data Message Rate, Resolution/Message Length fields

General Solution Criteria

Criteria	Ref	Value
Wireless networking standard (if used)		802.11a,b,g: WECA-WiFi (star) 802.15.1: Bluetooth (star) 802.15.3: WiMedia (star) 802.15.4: ZigBee (star, self-organizing mesh)
Frequency Band	IEEE Standards Documents	802.11a: 5.2, 5.7 GHz U-NII 802.11b,g: 2.4 GHz ISM 802.15.1: 2.4 GHz ISM 802.15.3: 2.4 GHz ISM 802.15.3a: 3.1 to 10.6 GHz 802.15.4: 868/915 MHz, 2.4 GHz ISM
Network Throughput Bandwidth of AP/Gateway Node at 100% duty cycle. (i.e., no energy conserving sleep modes, mains power) (Shared Resource among all nodes in network)	IEEE Standards Documents	Raw / Sustained 802.11a: 54 Mbps / ~20-24 Mbps 802.11b: 11 Mbps / ~4-5 Mbps 802.11g: 54 Mbps/ ~20-24 Mbps 802.15.1: 1Mbps/ 434kbps (sym.) ~723kbps (asym.) 802.15.3: 54 Mbps / ~30 Mbps 802.15.3a: 100, 200 Mbps; 480Mbps-optional 802.15.4: 250 kbps / ~115 kbps @2.4 GHz 40 kbps / ~ 19.6 kbps @915 MHz 20 kbps / ~ 9.6 kbps @868 MHz

General Solution Criteria

Criteria	Ref	Value
Signal Acquisition (ability to “lock on” to a signal and process data) Synch Preamble Length		802.11a: 10 short + 2 long symbols (16 μ s total) 802.11b: 128 bits (144 μ s) 802.11g: 128 bits (144 μ s) 802.15.1: 4 +64 bits (802.15.3: 10 symbols (0.91 μ s) 802.15.4: 32 bits (1600/800/128 μ s)
Jamming Resistance Minimum Adjacent; Alternate Channel Rejection (dB) [Alternate = 2 nd nearest channel]		802.11a: -1; 15 @ 54 Mbps / 13; 29 @ 12 Mbps 802.11b: 35; ns dB @ 11 Mbps 802.11g: 802.15.1: 0; 30 802.15.3: 19; 35 dB @ 55 Mbps / 33; 48 @ 11 Mbps 802.15.4: 0; 30 dB (all)
Intermediation Resistance		Not specified

General Solution Criteria

Criteria	Ref	Value
Interference & Susceptibility		802.11a: 802.11b: 802.11g: 802.15.1: 802.15.3: 802.15.3a: must avoid 900 MHz, 2.4 or 5 GHz UNII bands 802.15.4:
Electromagnetic Compatibility		802.11a: no issues for operation within regulatory limits 802.11b: no issues for operation within regulatory limits 802.11g: no issues for operation within regulatory limits 802.15.1: no issues for operation within regulatory limits 802.15.3: no issues for operation within regulatory limits 802.15.3a: no issues for operation within regulatory limits 802.15.4: no issues for operation within regulatory limits

General Solution Criteria

Criteria	Ref	Value
<p>Data Latency (ms) [as low as 10 ms]</p> <p>Beacon Interval</p>	<p>IEEE Standards Documents</p>	<p>802.11x: $1.024 \bullet N$ [N=1,2...$2^{16}-1$], ~100 ms typical default 802.15.1: 0.625 802.15.3: 0.512 (short frame) or 65.535 (long frame) 802.15.4: $15.36 \bullet 2^N$ [N=0,1..14] (+1.2x per multi-hop, on avg.) wake-up transition limited in some non-beacon scenarios 8 symbol CCA is minimum if transceiver is already active</p>
<p>Resolution/Message Length (bits/word) [at least 32 bits]</p> <p>Worst-case available payload per packet</p>	<p>IEEE Standards Documents</p>	<p>802.11a: 4095 bytes 802.11b: 2304 bytes 802.11g: 4095 bytes 802.15.1: 0-2745 bits 802.15.3: 0-2044 bytes 802.15.4: 0-103 bytes</p>
<p>Data Message Rate (Bytes/sec)</p> <p>One max. data packet payload per frame (from one node)</p>	<p>IEEE Standards Documents</p>	<p>802.11a: $\leq 3,999,023$ (1 put per N=1 for 54 Mbps) 802.11b: $\leq 1,125,000$ (1 put per N=2 for non-delayed beacons) 802.11g: $\leq 3,999,023$ (1 put per N=1 for 54 Mbps) 802.15.1: $\leq 90,000$ 802.15.3: $\leq 3,992,188$ (1 put/short frame), stream modes higher 802.15.4: $\leq 6,700$ (≤ 103 bytes per 15.36 ms beacon)</p>

General Solution Criteria

Criteria	Ref	Value
<p>Number of Sensors per Access Node [up to (at least) 64]</p>	<p>48 bit address fields</p> <p>Apple Airport Extreme</p> <p>IEEE Standards doc.</p> <p>IEEE Standards doc.</p>	<p>802.11x: limited by vendor-specific resources in AP and/or application tolerance of access contention.</p> <p>802.11g: 50 (for example)</p> <p>802.15.1: 7 (active)</p> <p>802.15.3: 254</p> <p>802.15.4: 254 (star), 65,500 (mesh)</p>
<p>Transmission Range (indoor) (meters)</p>	<p>Atheros</p> <p>^dCisco Aironet 350</p> <p>^aNEAsia ; ^bApple</p> <p>^oS Oceana Sensor</p>	<p>802.11a : 7 @ 54 Mbps, 69 @ 6 Mbps; +14 dBm TX</p> <p>802.11b: 39@11Mb/s, 107@1Mb/s; +20dBm, 2.2dBi diversity ant.</p> <p>802.11g: ^a12m / ^b15m @ 54 Mbps; +15 dBm TX</p> <p>802.15.1: ^o10m @ 720kbps; +0 dBm TX</p> <p>802.15.3: 10m @ 54 Mbps;</p> <p>802.15.4: 10m @ 250 Kbps; +0 dBm TX</p>
<p>Transmission Range (outdoor) (meters) [up to 1 km]</p>	<p>^cCisco350 Wireless Bridge</p> <p>^dCisco Aironet 350 AP</p>	<p>802.11b: up to ^c29 km @ 11Mbps, 40 km @ 2Mbps pt-2-pt</p> <p>802.11b: 244m@11Mbps, 610m@1Mbps; +20dBm, 2.2dBi diversity</p> <p>802.15.1: 30m</p> <p>802.15.3: 30m, up to 70m</p> <p>802.15.4: 30m typ, up to 75m @+0 dBm, 300m @+20 dBm</p>

Atheros - <http://www.atheros.com/AtherosRangeCapacityPaper.pdf>

NEAsia - http://neasia.nikkeibp.com/200211/inst_214613.html - “~50% greater range indoors at 2.4 GHz than 5 GHz“

Apple - <http://www.apple.com/airport/specs.html>

^cCisco - http://www.cisco.com/en/US/products/hw/wireless/ps458/products_data_sheet09186a008008883c.html

^dCisco - http://www.cisco.com/en/US/products/hw/wireless/ps458/products_data_sheet09186a008009247c.html

General Solution Criteria

Criteria	Ref	Value
Data Verification	IEEE Standards Documents	802.11a: 32 bit CRC (frames), 16 bit CRC (headers) 802.11b: 32 bit CRC (frames), 16 bit CRC (headers) 802.11g: 32 bit CRC (frames), 16 bit CRC (headers) 802.15.1: 16 bit CRC 802.15.3: 32 bit CRC 802.15.4: 16 bit CRC
Data Authentication	IEEE Standards Documents	802.11x: Open System, Shared Key 802.15.1: <i>128 bit symmetric key</i> 802.15.3: CTR+CBC 802.15.4: CTR, CBC-MAC, CTR+CBC
Data Encryption	IEEE Standards Documents	802.11b: WEP 40 (128 is commercially available) 802.11g: WEP 64,128 802.15.1: <i>Up to 128 bit streaming cipher</i> 802.15.3: AES-128 802.15.4: AES-128

General Solution Criteria

Item	Ref	Value
Peer to Peer (Ad-Hoc)	IEEE Standards Doc	YES (802.15.4, 802.15.3, 802.11)
Master/Slave Nodes	IEEE Standards Doc	YES (all)
Transmit Only nodes	IEEE Standards Doc	NO
Receive Only nodes	IEEE Standards Doc	Not prohibited
Bi-Directional nodes	IEEE Standards Doc	YES (all)
Computational nodes		Allowed (Application Layer function)
Repeater nodes	IEEE Standards Doc	YES (802.15.4)
Display nodes		Not prohibited (Application Layer function)

General Solution Criteria

Item	Ref	Value
Master Redundancy		Not specified
Multiple Access		802.11a,b,g: CSMA/CA 802.15.1: Polling 802.15.3: CSMA/CA + opt. TDMA in CTA 802.15.4: CSMA/CA + opt. TDMA in GTS
Bit Error Rate SNR required for BER=10 ⁻⁴	Estimated using BER vs. SNR graph from P802.15.4d18 Annex E (see slide #38)	802.11a: not available 802.11b: ~1.0, 4.5, 3.5, 7.0 dB { @ 1, 2, 5.5, 11 Mb/s} 802.11g: not available 802.15.1: ~12.5 dB 802.15.3: ~11.5 dB (22 Mbps) 802.15.4: ~0.2 dB (2.4 GHz)
Message Error Rate SNR required for 1% MER of N_bytes long message Using the formula (1-MER) = (1-BER) ^{8*N_bytes}	Estimated using BER vs. SNR graph from P802.15.4d18 Annex E (see slide #38) for comparison only	802.11a: <10%, 1000 bytes @ sensitivity (depends on rate) 802.11b: <3%, 400 bytes @ sensitivity (depends on rate) 802.11g: <10%, 1000 bytes @ sensitivity (depends on rate) 802.11b: [1024 bytes, BER~1e-6] SNR~7-8 dB @ 11 Mb/s [1024 bytes, BER~1e-6] SNR~3-4dB 802.15.1: [1024 bytes, BER~1e-6] SNR~14-15 dB 802.15.3: [1024 bytes, BER~1e-6] SNR~13-14 dB @ 22Mb/s 802.15.4: [22 bytes, BER~6e-5] SNR~0-1 dB @250Kb/s [1024 bytes, BER~1e-6] SNR~1-2 dB @250 Kb/s

Additional & Optional Features Supported

Item	Ref	Value
Undetected Message Error Rate	802.15.3 PAR	802.11x: not specified 802.15.1: not specified 802.15.3: <0.08% 802.15.4: not specified
Other additional & optional features		

IEEE Standards Document Reference List

ANSI/IEEE Std 802.11, 1999 Edition

IEEE Std 802.11a-1999

IEEE Std 802.11b-1999/Cor 1-2001

Draft IEEE Std 802.11g/D7.0, Mar 2003

IEEE Std 802.15.1TM-2002

Draft P802.15.3/D16, February 2003

Draft P802.15.4/D18, February-2003