INSTEON®

WHITEPAPER: Compared

INSTEON

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Preface to the Second Edition

Since the first edition of this white paper in January 2006, INSTEON® has been deployed in over a million nodes around the world in hundreds of different products. With feedback from the real world, INSTEON has refined the technology to make it even more robust, reliable and low-cost.

Networking is now a way of life, evolving organically much as life itself. Life, though, started "at the bottom,“ with only single-celled organisms existing for billions of years before more complex plants, animals and ecosystems evolved. Our communication networks are more like a nervous system for an already complex civilization. These networks are evolving in a "middle out" fashion, starting with moderate-bandwidth computer networking and working upward to broadband media networking and downward to "networking the small stuff."

Transmission of broadband media requires sophisticated networking protocols to support the high speeds needed for massive data transport. If the payload is television, then errors in transmission can be acceptable and compression which compromises the quality of the original media is tolerable in order to conserve bandwidth. For computer networking, errors in file transmission are normally unacceptable even though files can be large; thus much effort has gone into network infrastructure which gets packets through the network and accurately reassembled no matter what happens along the way. Either way, high-speed or high-reliability, the solutions come at a price. The networking protocols are complex and require intricate hardware and software to implement.

In contrast, the "small stuff," such as light switches, thermostats, sensors, appliances and even light bulbs themselves still linger without benefit of networked control and sensing. By now it's clear that if a device consumes electrons, it should also process bits so that it can join an ecology of products that we use and interact with every day. Most of us are already carrying around a gadget that could report on the state of our stuff and allow us to control it—our smartphones. Why is it, then, that we still have to walk up to light switches in order to control them?

The answer is that there has not been a networking protocol that is at the same time low-cost and reliable enough to be built into common devices like light switches or even light bulbs. INSTEON fits that bill. It is reliable because it does not depend on signaling over the powerline alone or over the airwaves alone, but uses both media at once. It is low-cost because it uses a low data rate, properly sized for command and control, with no pretensions of carrying massive amounts of data.

Furthermore, the low data rate enables *simulcasting* (synchronous transmission of identical signals by all INSTEON devices within range), so that powerline and radio signals benefit from increased signaling energy over their respective media, without infringing regulatory limits. Simulcasting radically increases reliability, but would not be practical at high data rates. So, a properly chosen data rate for command and control enables *both* low-cost and reliability—properties that are not simultaneously achievable with more complex networking protocols.

Despite its low data rate, INSTEON is *fast* for its intended sensing and control mission. That is because it is not a routed network that sends specific commands from controllers to numerous responders. Instead, a controller merely broadcasts a notification that a certain button has been pushed and all responders that have previously been associated with that button resume the state they were in when the association was first established. Controllers do not necessarily need to know the capabilities of the devices they operate and the response by the controlled devices is virtually instantaneous (normally within 50-100 milliseconds). For insurance, controllers do follow up group broadcast commands with individual "clean up" messages that each affected device must acknowledge, but in practice the insurance is seldom needed.

Even with its dual-mesh, simulcasting and state-restoration architectural advantages, INSTEON would remain a theoretical "wannabe" were it not for being tested in the crucible of high-volume global deployment and user acceptance. Both the powerline and airwaves are dynamic, hostile environments for signaling, fraught with impairments that come and go unpredictably in the real world. Over the past six years, initial versions of INSTEON have been superseded by numerous improvements, albeit with backward-compatibility protecting consumers' investments in the installed base. These lessons have forged INSTEON into a practical technology that is ready for deployment from millions of nodes into billions or even tens of billions of installations around the world.

Other protocols have been deployed in recent years and many more are on the drawing boards in hopes of becoming adopted by the marketplace. But it is still early in the game. INSTEON can coexist with other low-level, high-volume networks, at the very least because it does not interfere with them. There is already control software that is agnostic as to what physical path or signaling protocol connects sensors and actuators, but in the long run, the marketplace will be very sensitive to the reliability and cost benefits that INSTEON alone enjoys.

The transition from commonplace manual control to richly interconnected products of every sort will only happen once on Earth. The decision time is at hand—INSTEON is fully evolved and ready to occupy that enormous niche at the bottom of the food chain right now.

The following white paper details the case for these claims and contains updated information regarding the technologies to which it compares INSTEON.

Introduction

Wouldn't it be great if…

- You arrive home and the lights come on, the door unlocks and the thermostat adjusts.
- On a hot day, your blinds automatically close and fans cool the house before your air conditioner comes on, reducing your electric bill.
- Your smart microwave oven downloads new cooking recipes.
- You can use your cell phone to check if you left the garage door open and close it if you did.
- Your cell phone receives a text message if there is water in the basement.
- When you watch a movie, the lights dim, the blinds close and your TV automatically turns on the surround sound amplifier.

These are just a few of the scenarios that become possible when everything that is plugged in or battery-operated in your home can share information on a network. But what kind of network does it take to link together commodity devices like light switches, door locks, remote controls and thermostats?

We are all familiar with other kinds of networks. There are well over a billion personal computers in use around the world and most of them are connected to the global Internet. We use wireless WiFi networking in 80% of our homes and at an ever-increasing number of commercial "hotspots" around the world. And we actually have more cell phones than people. But light switches, door locks, thermostats, clocks, smoke detectors, security sensors and remote controls cannot talk to one another, because the networks that share computer data or connect cell phones together are far too complex and expensive to be built into *infrastructure* devices that only cost a few dollars.

INSTEON home networking technology fills this gap, because INSTEON embodies the *optimum* combination of simplicity, affordability and reliability. Created by SmartLabs, Inc., the world's leading authority on the connected home, INSTEON grew out of 13 years of experience delivering real-world home control products to consumers and professional installers all around the world. Since its introduction in 2005, millions of INSTEON-powered devices have been deployed around the world.

In 2001, when the engineers at SmartLabs laid down the architecture of INSTEON, they were well aware of efforts by others to bring about the home of the future. X10, for example, was being used by lots of "gadgetologists" to control lights and appliances, but the aging X10 protocol was simply too limiting, with its tiny command set and unacknowledged, 'press and pray' signaling over the powerline.

The INSTEON team knew that a common pitfall for new technology is overdesign—engineers often just can't resist putting in all the latest wizardry. But with added performance, cost goes up and ease-of-use goes down. A classic example was CEBus, designed by a committee of experts who wanted CEBus to be a networking panacea for everything that uses electricity. Even though CEBus did become an *official* standard (EIA-600), developers never incorporated it into mainstream real-world products.

The engineering and marketing teams at INSTEON carefully evaluated radio-only communication protocols, such as Z-Wave and ZigBee, but chose not to go down that path. Those protocols not only require complex routing strategies and a confusing array of different types of network masters, slaves and other modules, but radio alone suffers reliability problems when installed in reinforced concrete buildings, outside stucco walls, when blocked by metal objects or installed in metal switch junction boxes or other RF-blocking locations.

Other networking candidates were non-starters as well. Bluetooth radio has too short a range, WiFi radio is too expensive and too complicated and high-speed powerline protocols are far too complex to be built into high-volume, low-cost wired or battery-operated devices in the home. Overall, it seemed that everything proposed or available was too overdesigned and therefore would cost far too much to become a commodity in the global consumer marketplace. The solution, INSTEON, would have to be created from the ground up.

SmartLabs needed a technology that would embody the ideal home networking infrastructure:

- Instantly responsive
- Easy to install
- Simple to operate
- Reliable
- Affordable

This white paper explains how INSTEON achieves these ideals and contrasts INSTEON with other networking technologies proposed for home control. In particular, it compares INSTEON in detail with both Z-Wave and ZigBee.

Many familiar products can be improved by the ability to interact over a network and a myriad of new products become possible when designers can routinely connect them to a simple, affordable and reliable "nervous system" in the home. As this white paper will show, the ideal embodiment of this infrastructure is INSTEON—the right home-control networking technology for the 21st century.

INSTEON Overview

INSTEON enables simple, low-cost devices to be networked together using the powerline, radio or both. All INSTEON devices are peers, meaning that any device can transmit, receive or repeat[1] other messages without requiring a master controller or complex routing software. Adding more devices makes an INSTEON network more robust, because INSTEON devices repeat each other's messages by simulcasting them at precisely the same time, so with more devices the INSTEON signal gets stronger. On the powerline, INSTEON devices can also be compatible[2] with legacy X10 devices.

First deployed in 2005, there are now millions of INSTEON nodes in use around the world in many different products, including dimmers and switches, handheld and tabletop remotes, thermostats, sprinkler controllers, energy monitoring devices, sensors and low-voltage input/output interfaces. INSTEON networks easily connect to other, larger networks, such as LANs and Wi-Fi. Many different user interfaces, including smartphones, PCs and third-party controllers, can manage an INSTEON network. Applications running on such devices not only can talk to INSTEON products, but can interoperate with cameras, sensors and other devices using different networking protocols, including TCP/IP, ZigBee and Z-Wave. See www.insteon.com for more information on the latest INSTEON product offerings.

This section further explains why INSTEON has the properties it does without going into the details. For a comprehensive introduction to INSTEON, see the white paper *INSTEON, the Details*, available at www.insteon.com. For complete information, consult the *INSTEON Developer's Guide*.

Hallmarks of INSTEON

These are the project pillars that SmartLabs decided upon to guide the development of INSTEON. Products networked with INSTEON had to be:

Reliable

An INSTEON network becomes more robust and reliable as it is expanded because INSTEON devices repeat1 messages received from other INSTEON devices. Dual-mesh communications using both the powerline and the airwaves ensures that there are multiple pathways for messages to travel.

Affordable

INSTEON software is simple and compact because all INSTEON devices send and receive messages in exactly the same way, without requiring a special network controller or complex routing algorithms. The cost of networking products with INSTEON is held at an absolute minimum because INSTEON is designed specifically for home control applications, not for transporting large amounts of data.

Instantly Responsive

INSTEON devices respond to commands with no perceptible delay. INSTEON's signaling speed is optimized for home control—fast enough for quick response, while still allowing reliable networking using low-cost components.

Secure

INSTEON's first level of security is the same as that relied on for centuries—physical possession of devices—just as with mechanical locks and keys. An eavesdropper would need knowledge of the INSTEON addresses of your devices and the low-level INSTEON firmware engine masks those addresses. At a higher level, INSTEON extended messages allow for encryption using global standards such as AES-256, the same as with other protocols.

Easy to Install

Installation in existing homes does not require any new wiring, because INSTEON products communicate over powerline wires or they use the airwaves. Users never have to deal with network enrollment issues because all INSTEON devices have an I.D. number pre-loaded at the factory—INSTEON devices join the network as soon as they're powered up.

Simple to Setup Control Relationships

Getting one INSTEON device to control another is very simple:

Option 1: Manual Linking

- Just press and hold a button on each device for a few seconds and they're linked.

Option 2: Software Linking

- Create links via any one of dozens of apps for smartphones/tablets, PCs or Macs.

How INSTEON Works

There are three fundamental differences between INSTEON and *all* of other command and control networks.

- INSTEON is a dual-mesh network (two uncorrelated media).
- INSTEON propagates messages by simulcasting.
- INSTEON utilizes Statelink.

INSTEON is a Dual-Mesh Network

There are 115 million households in the U.S. Virtually all have powerline wiring and the ISM (industrial, scientific, medical) radio bands are freely available for unlicensed home use, so utilizing communications over both the powerline and over the airwaves makes the most sense for command and control networking.

Single media communication exclusively over powerline or radio bands is fraught with problems. The FCC requires that radio devices using the ISM bands must be able to tolerate interference from other devices and there are many ways in the home that radio signals can be attenuated and reflected. The powerline is notorious for electrical noise and phase bridging problems (see below) can prevent signals from half of the circuits in a house from reaching the other half.

INSTEON solves the single media signaling problems because it is a *dual-mesh* network. As shown in the diagram below, INSTEON devices can communicate with each other using *both* radio and the powerline.

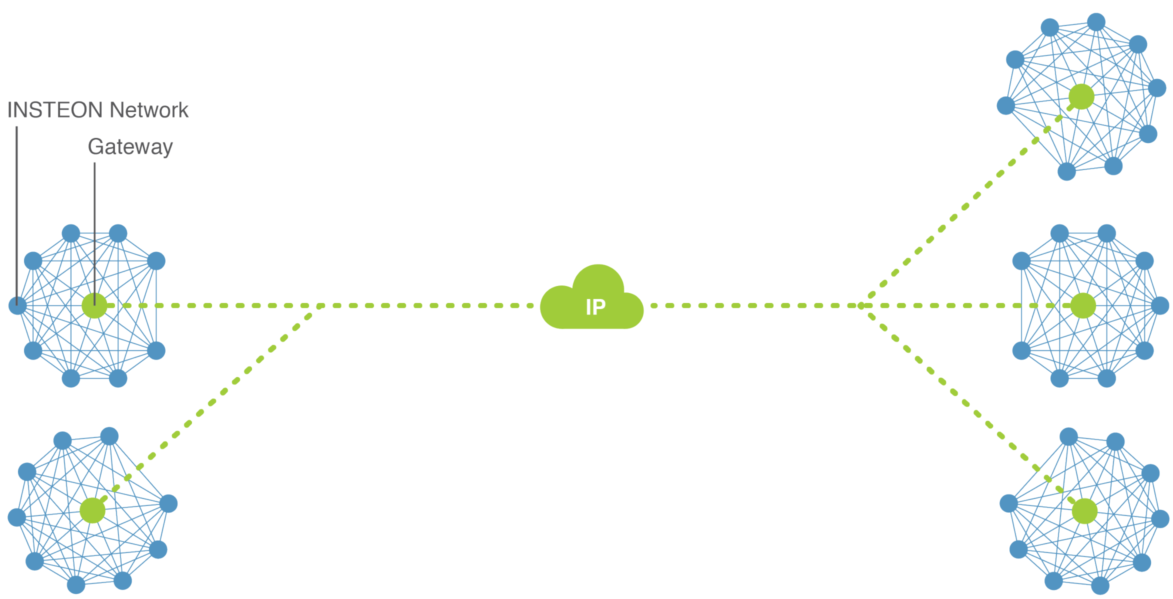
All INSTEON devices that are connected to the powerlines communicate using both INSTEON powerline and RF (legacy powerline only devices exist). Battery-powered INSTEON devices communicate with dual-band devices using INSTEON RF.

INSTEON dual-band devices solve a significant problem encountered by networking technologies that can only communicate via the powerline. Electrical power is most commonly distributed to homes in North America as split-phase 220-volt alternating current (220 VAC). At the main electrical junction box to the home, the single three-wire 220 VAC powerline is split into a pair of two-wire 110 VAC powerlines, known as Phase 1 and Phase 2. Phase 1 wiring usually powers half the circuits in the home and Phase 2 powers the other half.

The problem is that powerline signals originating on one phase needing to reach a receiver on the other phase are severely attenuated, because in many cases there is no direct circuit connection for them to travel over.

A traditional solution to this problem is to connect a signal coupling device between the powerline phases, either by hardwiring it in at a junction box or by plugging it into a 220 VAC outlet. INSTEON automatically solves the powerline phase coupling problem through the use of dual-band INSTEON devices—INSTEON RF messages automatically couple the phases when received by a dual-band device on the "other" phase.

As shown in the diagram below, devices on INSTEON networks can also interface with the larger world. When suitably equipped with a dedicated serial interface, such as U.S.B, RS232, Ethernet or WiFi, INSTEON devices can also interface with computers, smartphones and other digital equipment. Serial communications can bridge networks of INSTEON devices to otherwise incompatible networks of devices in a home, to computers, to other nodes on a local-area network (LAN) or to the global Internet. Such connections to outside resources allow networks of INSTEON devices to exhibit complex, adaptive, *people-pleasing* behaviors.



INSTEON Simulcasts Repeated Messages

INSTEON devices repeat[1] each another's INSTEON messages by simulcasting them in precise timeslots synchronized to the powerline zero crossing. To avoid runaway signals, each message is assigned a maximum number of times to be repeated. Each repeated message then contains how many repeats remain until it reaches zero. Presently, the maximum number of repeats can be set to 0, 1, 2 or 3. While all INSTEON devices can act as repeaters, in virtually all situations battery-powered devices do not to conserve battery power.

INSTEON devices automatically and immediately act as repeaters upon power-up — they do not need to be specially installed using some network setup procedure. Adding more devices not only increases the strength of the simulcast signal, but also increases the number of available pathways for messages to travel. This *path diversity* results in highly reliable messaging, so the more devices in an INSTEON network, the better.

Simulcasting does not require routing of the message. This makes the networking infrastructure much simpler and less expensive than a routed network. Also, the simulcast propagation automatically produces simultaneous response at all responders. This means that responders don't fire at different times creating a "popcorn" effect.

INSTEON Utilizes Statelink

Statelink is a simple, yet powerful tool. Instead of using "commands" to get responders to their desired states, INSTEON simply signals the responder to "recall" the state at which it was at when added to the "scene." Therefore, a generic signal can be sent by any controller resulting in any number of responders recalling their scene states even though the products might vary greatly (e.g. thermostats, lights, pumps, clocks, security systems, etc.).

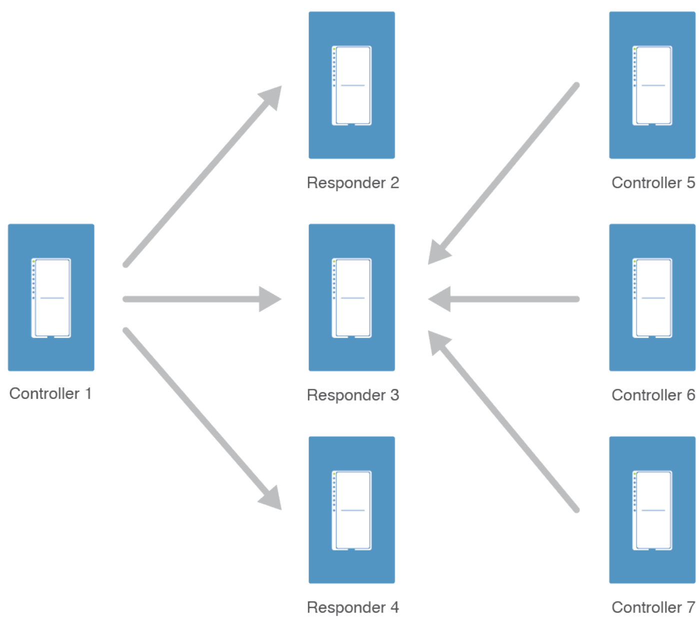
Since these scene messages are generic in nature, all INSTEON products can both send and respond to them. This fundamentally guarantees that products are both forwards and backwards compatible—a virtually priceless advantage.

Another enormous advantage of Statelink is that when combined with simulcasting, they create an infrastructure that scales to very large installations. INSTEON installations with over 400 nodes are relatively common.

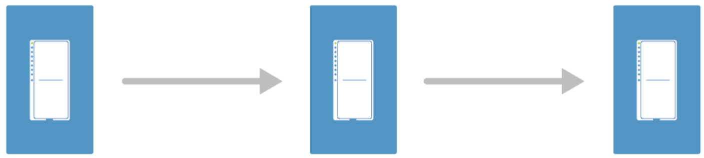
INSTEON is a Peer-to-Peer Network

All INSTEON devices are peers, meaning that any device can act as a controller (sending messages), responder (receiving messages) or repeater[1] (relaying messages).

This relationship is illustrated in the figure below, where INSTEON device **1**, acting as a controller, sends messages to INSTEON devices **2**, **3** and **4** acting as responders. INSTEON devices **5**, **6** and **7** acting as controllers can also send messages to a single INSTEON device **3** acting as a responder.



Any non-battery-powered INSTEON device can repeat[1] messages, as with device **B** below, which is shown relaying a message from device **A** acting as a controller to device **C** acting as a responder.



INSTEON Facilitates Product Development

INSTEON, with its emphasis on simplicity, reliability and low-cost, is optimized as an *infrastructure* network for home integration and control. Common devices in the home, such as light switches, door locks, thermostats, clocks and entertainment systems currently do not communicate with one another. INSTEON can change all that.

When devices are networked together, there is a potential for coordinated, adaptive behavior that can bring a new, higher level of comfort, safety and convenience to living. But networking devices together cannot by itself change the behavior of the devices. It is application-level software, created by product developers, that transforms a network of previously unrelated devices into a coordinated, adaptive, lifestyle-enhancing system.

INSTEON Specifications

INSTEON is a true peer-to-peer dual-mesh network. Its most important property is its simplicity.

INSTEON messages are fixed in length and synchronized to the AC powerline zero crossings. Because messages propagate by synchronous simulcasting, no network controllers or routing tables are necessary—a three-byte source and destination address in each message suffices.

Optimized for home command and control, INSTEON allows infrastructure devices like light switches, clocks, thermostats, security sensors and remote controls to be networked together at low-cost. In turn, these devices can appear as nodes on larger networks, such as WiFi LANs, the Internet, telephony and broadband entertainment distribution systems, because INSTEON can connect to them using internetworking devices.

The following table shows the main features of INSTEON at a glance.

INSTEON Property	Specification
Network	Dual-mesh (RF and powerline)
	Peer-to-peer
	Mesh topology
	Unsupervised
	No routing tables
Protocol	All non-battery-powered devices are two-way repeaters[1]
	Messages synchronized to powerline
	Repeated messages are simulcast

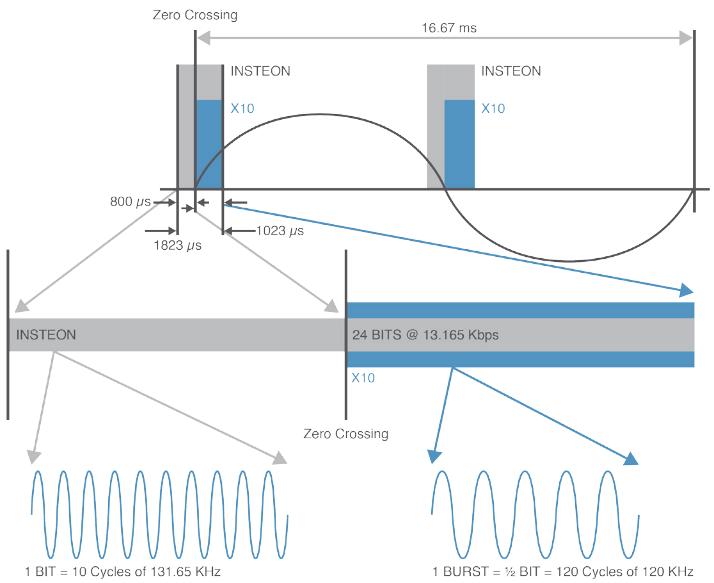
INSTEON Property	Specification	
	Message error detection Messages acknowledged Retry if not acknowledged	
Data Rate	Instantaneous powerline	13,165 bits/sec
	Sustained powerline	2,880 bits/sec
	Instantaneous RF	38,400 bits/sec
Message Types	Standard	10 bytes
	Extended	24 bytes
Message Format	From address	3 bytes
	To address	3 bytes
	Flags	1 byte
	Command	2 bytes
	User data	14 bytes (Extended Messages)
	Message integrity	1 byte
Devices Supported	Unique I.D.s	16,777,216
	Commands	65,536
	Members within a group	Limited only by memory
INSTEON Engine Memory Requirements	RAM	80 bytes
	ROM	3K bytes
Typical Application (Light Switch, Lamp Dimmer) Memory Requirements	RAM	256 bytes
	EEPROM	256 bytes
	Flash	7K bytes
Device Installation	Plug-in Wire-in Battery-operated	
Device Setup	Linking via button or software (smartphone, PC or controller)	
Security	Physical device possession Address masking Encrypted message payloads	
X10 Compatibility[2]	INSTEON devices may send and receive X10 commands	
Powerline Physical Layer	Frequency	131.65 KHz

INSTEON Property	Specification	
RF Physical Layer	Modulation	BPSK
	Min. transmit level	3.16 Vpp into 5 Ohms
	Min. receive level	10 mV
	Phase bridging	INSTEON RF or hardware
	Frequency	915.00 MHz in U.S. 869.85 MHz in Europe 921.00 MHz in Australia
	Modulation	FSK
	Sensitivity	-103 dbm
	Range	150 ft unobstructed line-of-sight

INSTEON Packet Timing

All INSTEON powerline packets contain 24 bits. Since a bit takes 10 cycles of 131.65 KHz carrier, there are 240 cycles of carrier in an INSTEON packet. An INSTEON powerline packet therefore lasts 1.823 milliseconds.

The powerline environment is notorious for uncontrolled noise, especially high-amplitude spikes caused by motors, dimmers and compact fluorescent lighting. This noise is minimal during the time that the current on the powerline reverses direction, a time known as the powerline zero crossing. Therefore, INSTEON packets are transmitted during the zero crossing quiet time, as shown in the figure below.



The top of the figure shows a single powerline cycle, which possesses two zero crossings. An INSTEON packet is shown at each zero crossing. INSTEON packets begin 800 microseconds before a zero crossing and last until 1023 microseconds after the zero crossing.

INSTEON Powerline Data Rates

As explained at greater length in *INSTEON, the Details* (available at www.insteon.com), INSTEON Standard messages contain 120 raw data bits and require 5 zero crossings or 41.667 milliseconds to send. Extended messages contain 264 raw data bits and require 11 zero crossings or 91.667 milliseconds to send. The *raw* s*ustained* INSTEON bitrate is therefore 2880 bps (bits per second) for either kind of message.

However, the INSTEON protocol waits for one additional zero crossing after each Standard message and for two additional zero crossings after each Extended message to allow for transmitter 'politeness' and possible RF message transmission. Therefore, the *actual sustained* bitrate is 2400 bps for Standard messages or 2437 bps for Extended messages, instead of the 2880 bps second it would be without waiting for the extra zero crossings.

INSTEON Standard messages contain 9 bytes (72 bits) of usable data, not counting packet sync and start code bits, nor the message integrity byte. Extended messages contain 23 bytes (184 bits) of usable data using the same criteria. Therefore, the *usable data* bitrates are further reduced to 1440 bps for Standard messages and 1698 bps for Extended messages. Counting only the 14 bytes (112 bits) of user data in Extended messages, the *user data* bitrate is 1034 bps.

These data rates assume that messages are sent with max. hops set to zero and that there are no message retries. They also do not take into account the time it takes for a message to be acknowledged. The table below shows net data rates when multiple hops and message acknowledgement are taken into account. To account for retries, divide the given data rates by one plus the number of retries (up to a maximum of five possible retries).

Condition			**Bits per Second**		
Max. hops	**ACK**	**Retries**	**Standard message (usable data)**	**Extended message (usable data)**	**Extended message (user data only)**
0	No	0	1440	1698	1034
1	No	0	720	849	517
2	No	0	480	566	345
3	No	0	360	425	259
0	Yes	0	720	849	517
1	Yes	0	360	425	259
2	Yes	0	240	283	173
3	Yes	0	180	213	130

INSTEON Comparisons

This section contains detailed comparisons of INSTEON to Z-Wave and ZigBee. Comparisons to other networking technologies are also included.

ZigBee

ZigBee is a routed radio networking standard developed by a group of ZigBee Alliance members (www.zigbee.org). ZigBee is the latest name in an effort begun in the mid 1990s originally called "HomeRF." Ratified in December 2004 and released to the public in June 2005, the ZigBee specification defines the Application/Framework and Network/Security layers built atop the pre-existing IEEE 802.15.4 radio standard. ZigBee was designed to be used in widely diverse of applications, ranging from battery-operated devices to commercial and industrial building management (see ZigBee Interoperability, below).

IEEE 802.15.4, which was completed in May 2003, defines a *Low-Rate Wireless Personal Area Network (WPAN)* that includes a direct sequence spread spectrum (DSSS) physical radio (PHY) layer and a media access control (MAC) software layer. Several chip vendors offer 802.14.4 radios that include microprocessors and 128K of onboard memory for the ZigBee stack. 802.15.4 radios also find uses in numerous non-ZigBee applications.

ZigBee's design goals were:

- A wireless network for industrial controls, medical devices, alarms, building automation and home automation;
- A self-organizing mesh network;
- A low data rate; and
- Low power consumption (greater than one-year battery life).

ZigBee has defined multiple kinds of devices, including

- Network coordinators, one per network, at the root of the network tree;
- FFDs (full-function devices), which can be routers; and
- RFDs (reduced-function devices), which cannot be routers.

Only FFDs can form a mesh network, so ZigBee also defines a *star* network that can include RFDs at the edge of the network and a hybrid network called a *cluster tree*. Within these networks there can be beaconing or non-beaconing in order to support battery-operated devices that wake up intermittently.

ZigBee 802.15.4 radios can operate at 2.4 GHz worldwide or at 915 MHz in the U.S. and 868 MHz in Europe, although the two lower frequencies have not found market acceptance.

ZigBee product developers must be members of the ZigBee Alliance. An entry-level *Adopting Membership* is $3,500 per year, but participation in ZigBee standards setting requires a *Participating Membership* for $9,500 or a *Promoter Membership* for $50,000 annually.

How ZigBee Works

ZigBee, so named because its messages zigzag around like a bee, is a routed radio-only network. ZigBee uses IEEE 802.15.4 spread spectrum radios, but with extensive additional software specified by the ZigBee Alliance.

IEEE 802.15.4 Radios

The IEEE 802.15.4 Low-Rate Wireless Personal Area Network (WPAN) standard, released in May 2003, defines the Physical (PHY) and Media Access Control (MAC) layers for Direct Sequence Spread Spectrum (DSSS) radios.

In a given market, these radios can operate at two distinct frequencies, 868 MHz and 2.4 GHz in Europe and 915 MHz and 2.4 GHz in the U.S. and some other countries. The data rate varies depending on the frequency. In the table below, the payload data rates have been calculated assuming 15 bytes of overhead per packet, although in practice the non-secure overhead can vary from 15 to 35 bytes (see below).

Property	Value		
Frequency	868 MHz	915 MHz	2.4 GHz
Region	Europe	U.S.	Worldwide
Channels	1	10	16
Modulation	BPSK	BPSK	O-QPSK
Bandwidth	600 KHz	1.2 MHz	2 MHz
Raw Data Rate	20 Kbps	40 Kbps	250 Kbps
9-byte payload data rate	8 Kbps	15 Kbps	94 Kbps
14-byte payload data rate	10 Kbps	19 Kbps	121 Kbps
23-byte payload data rate	12 Kbps	24 Kbps	151 Kbps

In a home environment, lower frequencies typically propagate two or more times farther than 2.4 GHz due to less absorption by construction materials. However, the market has chosen to produce only 2.4GHz products. Furthermore, should the market develop 868/915 radios they will not be able to communicate with the 2.4GHz products.

At the PHY level, 802.15.4 radios can perform receiver energy detection, link quality indication and clear channel assessment.

The MAC layer supports 64,000 nodes per network. All devices must have an 8-byte IEEE address, but 2-byte short addresses can optionally be allocated during specified network association and dissociation procedures.

802.15.4 defines both contention-free and contention-based channel access methods. For contention-free communications, an optional guaranteed timeslot (GTS) can be used for high priority messages, but the radios normally use CSMA-CD (carrier sense multiple access with collision detect) for contention-based messaging.

Packets are variable size, with a maximum length of 128 bytes or 104 bytes maximum payload. For battery operation, 802.15.4 defines an optional super-frame that allows low-power devices to wake up periodically.

Packet overhead (non-payload) data takes from 15 to 35 bytes, with an additional 7 bytes for optional security encryption, as shown in the following table.

Stack layer	Field	Size, bytes	Total bytes
PHY	Preamble	4	6
	Start of Frame	1	
	Frame Length	1	
MAC	Frame Control	2	9 - 29
	Data Sequence Number	1	
	Address Information	4 – 20	
	Frame Check Sequence	2	
Security	Frame Count	4	7
	Sequence Count	1	
	Integrity Code	2	

Other 802.15.4 Radio Software Stacks

There are multiple software stacks besides ZigBee available to implement wireless networks using 802.15.4 radios. An example is 6LoWPAN designed by the Internet Engineering Task Force (IETF), but many others are available from radio vendors. Some other 802.15.4 radio modules are: the Synapse SNAP stack, Nivis ISA100.11a, Nivis WirelessHART, the JenNet stack, the DigiMesh network protocol, the ECL EcoKit and MeshNetics' OpenMac.

Many manufacturers of products utilizing non-ZigBee 802.15.4 radios refer to their products as ZigBee compatible. This clearly leads to interoperability problems, not to mention marketplace confusion.

ZigBee Software

The ZigBee Alliance has defined Application/Framework and Network/Security software layers atop the radio PHY and MAC layers. The ZigBee specification was ratified December 14, 2004 and made available to the public in June 2005.

The network layer supports star, mesh and cluster-tree (hybrid star/mesh) network topologies. The mesh network is self-forming and self-healing with multiple routes for data. Network traffic can be intermittent, periodic or guaranteed timeslot for repetitive low-latency data.

Multiple network topologies are the consequence of supporting multiple kinds of physical and logical devices defined by ZigBee in order to reduce cost for at least some devices.

There are two physical ZigBee device types—full-function devices (FFDs) and reduced-function devices (RFDs). Typically line-powered, FFDs can communicate with all other FFDs and RFDs, they can act as network and link coordinators, they can discover other FFDs and RFDs and they can perform all RFD functions. RFDs are typically battery-powered and they can only be installed in star networks because they can only talk to an FFD network coordinator. RFDs often go to sleep to reduce battery drain; when they wake up they can determine if data is pending, request data from the network coordinator, transfer data from an application or search for available networks.

ZigBee logical device types include network coordinators, routers and end devices. Network coordinators initialize a ZigBee network, manage network nodes and store network node information. ZigBee routers transfer messages between paired nodes. ZigBee end devices can only be leaf nodes in a network because they do not participate in message routing.

The following table shows various software services that the ZigBee stack performs at various layers. This software is in addition to the software for managing the underlying 802.15.4 radios.

ZigBee Software Layer	Functions
MAC support	Send/receive data Manage transaction queue Perform network association Synchronize devices Scan radio channels Get communication status Manage parameters Manage beacon Sync without beacon Manage guaranteed timeslots Reset Manage device orphans Turn radio on/off
Network	Start network Join and leave network Configure new device Assign addresses Synchronize within a network Manage security Manage routing
Application Support	Discovery Binding
Security	Manage access control lists Manage packet freshness timers Manage 128-bit AES encryption

ZigBee Interoperability

ZigBee has aimed for a broad universe of applications, including data monitoring and control, structured wiring replacement, battery-operated devices, commercial and industrial building management and home automation.

To support these markets, ZigBee has formed a number of committees to develop public *Application Profiles* to define product properties required for different vendors to build interoperable devices. This is an intricate, ongoing task that can only be successful given perfect communication and planning amongst the committees. Accordingly, ZigBee allows vendors to create private profiles for their own purposes. The current list of public Application Profiles that ZigBee is working on or released is:

- Smart energy
- Building automation
- Remote control
- Home automation
- Telecommunications services
- Health care
- Retail services
- Light link

Products aren't necessarily interoperable across these profiles. In fact, products aren't necessarily interoperable across revisions within a profile.

ZigBee Certification

To earn certification for their products, vendors must be *Adopting Members* of the ZigBee Alliance, at a cost of $3,500 per year. There are three levels of certification:

- ZigBee-Compliant Platform, for chipsets or modules
- ZigBee Friendly, for devices using private Application Profiles
- ZigBee-Logo Certified, for devices using public Application Profiles

ZigBee charges $1,000 for Product Certification of a first product SKU (stock-keeping unit) and $500 for each SKU thereafter.

ZigBee Test Service Providers charge additional fees for performing the actual tests.

INSTEON Compatibility with ZigBee

INSTEON radio can coexist with ZigBee because INSTEON is narrowband at 915 MHz while ZigBee occupies 1.5 MHz at 915 MHz using direct sequence spread spectrum (DSSS) modulation. DSSS looks like noise to INSTEON receivers and INSTEON looks like a narrow signal at one frequency to ZigBee. 2.4 GHz devices like 802.15.4 ZigBee radios are invisible to INSTEON and vice-versa.

Because of non-interference, INSTEON and ZigBee devices can coexist in the same or neighboring installations. Indeed, they can even interoperate, given controller devices with network interoperation capabilities.

INSTEON Compared with ZigBee

There are several noteworthy differences between INSTEON and ZigBee that have consequences in the home control marketplace. The main differences are that:

- INSTEON is dual-mesh, ZigBee is radio only;
- INSTEON propagates messages by simulcasting, ZigBee routes messages;
- INSTEON messages are backwards and forwards compatible, ZigBee messages are specific to revision level and profile;
- INSTEON devices are peers, ZigBee has full-function devices and reduced-function devices;
- INSTEON requires no separate network enrollment step;

- INSTEON uses FSK radios in one band per market, ZigBee uses DSSS in two bands per market.

Taken together, these distinctions entail higher cost and complexity for ZigBee radio. Granting that the elevated cost buys ZigBee radio devices with somewhat higher performance than INSTEON radios, INSTEON's dual-mesh architecture provides a powerline backup that ZigBee can't rely on when its radio-only messaging does fail.

On balance, ZigBee's cost and complexity make it better suited for large industrial and commercial networks, whereas INSTEON is optimized for the home.

INSTEON Uses Both Powerline and Radio Communications

Radio communication is far from 100% reliable, as cell phone and WiFi users are frequently reminded from firsthand experience. ZigBee's single media design is clearly sub-optimal to INSTEON's dual-mesh design. Industry participants have come to recognize this fact. As such efforts are underway to resolve this deficiency by bridging to a powerline technology. These efforts will clearly lead to networking inefficiencies, additional hardware requirements and added costs. ZigBee's 802.15.4 radios, although sophisticated, are not perfect—sometimes a ZigBee radio message will not get through and then the only recourse is to retry. INSTEON, however, has backup—the powerline can go where radio may be blocked. This means that INSTEON radios can be simpler and lower cost than ZigBee radios and the software can occupy a smaller footprint while running on ultra-low-cost microcontrollers.

INSTEON Uses Simulcasting Instead of Routing

Conventional wisdom has it that network protocols must prevent messages from clobbering one another at all costs, with the result that system designers often choose message routing as the best way to achieve a well-behaved network. While this may be true for high-speed networks, at the modest data rates INSTEON requires for home command and control, more than one copy of a message can be sent in the same synchronized timeslot. Simulcasting of messages avoids any need for network controllers and routers and it has the added benefit that as more devices simulcast a message, more energy goes into sending that message, so the more likely it is for the message to get through.

INSTEON is a Peer-to-Peer Network

Because of the complexity of the ZigBee software stack, chips that contain it along with 802.15.4 radios typically have 128K bytes of onboard memory and a relatively high-performance microprocessor core. In an attempt to reduce the overall cost of a network of ZigBee devices, ZigBee has defined full-function devices (FFDs) and reduced-function devices (RFDs), with multiple stack protocols and options to support the different kinds of devices. Each ZigBee network must have at least one FFD to act as a network coordinator. Any RFDs must be at the perimeter of the network defined by the network coordinator and there is some danger that such leaf RFDs will reconnect to a different coordinator after signal loss.

INSTEON, thanks to the simplicity of simulcasting, does not have any of these problems. The full INSTEON engine, which is the same for *every* INSTEON device, takes up less than 3K bytes, leaving over 5K bytes for application code in an 8K byte microcontroller, more than enough for lamp dimmers and simple controllers.

INSTEON Requires No Network Enrollment

With a unique I.D. number assigned to every device during manufacture, INSTEON devices automatically join an INSTEON network and help with simulcasting repeated messages as soon as they are powered up. With no need for a separate network enrollment step, users only need to link button pushes on a controller with functions on a controlled device. This straightforward setup can be accomplished by anyone using a simple *Tap-Tap™* procedure or optionally using software.

INSTEON Radio Is Simpler

INSTEON uses proven FSK (frequency shift keying) radios at 915 MHz, while ZigBee uses complex DSSS (direct sequence spread spectrum) radios in two bands per market. FSK receivers are more than twice as sensitive as DSSS radios while only requiring one-fourth the silicon.

Even though ZigBee is not the only protocol used by 802.15.4 radios on the market, most chip vendors are currently only offering 2.4 GHz radios containing the ZigBee stack. Products using 868 MHz in Europe and 915 MHz in the U.S. have not appeared in the marketplace.

INSTEON uses a single frequency of 915 MHz, which has two advantages. 915 MHz propagates farther than 2.4 GHz in typical home environments, and WiFi, which already occupies the 2.4 GHz band at higher power, cannot interfere with INSTEON, although it might cause problems with ZigBee.

INSTEON versus ZigBee Comparison Table

The following table summarizes the differences between INSTEON and ZigBee.

Property	INSTEON	ZigBee
Media	Powerline and radio	Radio only
Module types	All are peers	Network coordinator (1 per network) Full-function device (FFD) Reduced-function device (RFD)
Network topology	Full mesh	Partial routed mesh – only FFDs are repeaters Partial star – RFDs are star networked each to a single FFD
RF interoperability	Yes, 915 MHz	No, 915 MHz and 2.4 GHz
Command interoperability	Yes, Statelink	No, 8 profiles and revisions thereof
Message propagation	Simulcasting repeaters[1]	Routing tables
RF data rate, bps	38.4K instantaneous at 915 MHz	20K instantaneous at 868 MHz 40K instantaneous at 915 MHz 250K instantaneous at 2.4 GHz
RF PHY	FSK in ISM Band	DSSS in two ISM bands
Powerline data rate, bps	13,165 instantaneous PL 2,880 sustained PL 1,440 standard msg payload 1,698 extended msg payload 1,034 user data	None
Powerline PHY	131.65 KHz carrier BPSK	None
X10 compatible[2]	Yes	N/A
Powerline phase bridging	RF or hardware	N/A
Acknowledged	Yes	Yes
Addressing	24-bit pre-assigned module I.D.	64-bit IEEE address

	(16,777,216 devices)	16-bit short address (65,536 devices)
Network enrollment	Automatic	Part of installation procedure
Groups	Databases in modules	?
Commands	2-byte (65,536)	Application profiles
Device types	3-byte (16,777,216)	Application profiles
Global clock	Powerline zero crossing	Optional beaconing
Retries	Yes	Yes
Message length	15, 33 bytes	Variable, 128 byte maximum
Collision avoidance	Yes	Yes
Triac xontrol	Yes	?
SRAM	256 bytes	?
Flash	4K x 14 bits (7K bytes)	128K bytes typical
EEPROM external	4K bytes	?
EEPROM internal	256 bytes	?
Watchdog	Yes	?

Z-Wave

Z-Wave® is a routed, radio-only network owned by Sigma Designs, Inc. (www.sigmadesigns.com), of Milpitas, CA. A public company (NASDAQ: SIGM), Sigma Designs purchased Z-Wave from ZenSys of Denmark, the originator of Z-Wave, on December 18, 2008.

Intended for wireless home control applications, Z-Wave has design goals similar in some respects to those of INSTEON:

- Low-cost
- Low power
- Reliable
- Easy network installation
- Easy association process
- No ongoing network management
- Product interoperability

Z-Wave sends messages using radio alone. If for any reason radio messaging fails, Z-Wave can't rely on the powerline to get messages through. Therefore, Z-Wave's designers were obliged to give it a number of relatively complex features in order to make it as reliable as they could.

Most notably, Z-Wave routes its messages through the network using a Source Routing Algorithm (SRA). The SRA requires message initiator devices to know the arrangement of other devices in the network (the topology) so that they can compute the best route for messages to travel. Maintaining and distributing a network topology database is an intricate software task, especially when some devices in the network are mobile. Therefore, to keep costs down, Z-Wave defines different kinds of devices, with the lowest-cost devices, called slaves, unable to initiate messages.

In contrast, INSTEON is a *dual-mesh* network, using both radio and powerline to back each other up. INSTEON does not route messages—it *simulcasts* them in precise, synchronized timeslots. Simulcasting is so much simpler than routing that all INSTEON devices can be low-cost peers, with no need for complex master controllers or simplified reduced-function devices.

See APPENDIX I — Z-Wave Usability Evaluation for a case study of some of the consequences of Z-Wave's network architecture choices.

To create a Z-Wave-certified product, developers must be Affiliate Members of the Z-Wave Alliance (www.z-wavealliance.org), which costs $300 per year. Manufacturers may conduct their own Self-certification Tests, but a Z-Wave Test Partner must validate these tests at a typical cost of $750 per product.

Z-Wave is covered by a U.S. Patent, number 6,879,806, issued April 12, 2005, titled System and a Method for Building Routing Tables and for Routing Signals in an Automation System, that covers some aspects of Z-Wave networking.

How Z-Wave Works

Intended for wireless home control applications, Z-Wave radio networking is designed for relatively few nodes (232 maximum, but manufacturers recommend no more than 30-50) that communicate on average every 5 to 15 minutes. Z-Wave messages are variable length, with a payload averaging 4 to 6 bytes. Message latency requirements are relaxed to 200 milliseconds or more.

Z-Wave Physical Layer

Z-Wave radios use an unlicensed carrier frequency of 908.42 MHz in the U.S., 868.42 MHz in Europe, 919.82 MHz in Hong Kong and 921.42 MHz in Australia. Data is modulated onto the carrier at 9600 to 100,000 bps using GFSK (Gaussian frequency shift keying).

Z-Wave Messaging

The minimum length of a properly formatted Z-Wave message is 9 bytes, but a routed message requires 12 bytes plus repeater data plus the payload.

The message protocol includes routing, frame acknowledgement, collision avoidance with random back off and a frame checksum with retransmission if necessary.

The Z-Wave network is self-organizing and self-healing. To achieve self-organization, Z-Wave nodes have software that discovers the node's neighbors and informs the network's Static Update Controller (SUC) about them. A Source Routing Algorithm (SRA) in devices capable of initiating communication finds message pathways and generates routes based on a network topology database. Self-healing requires software to dynamically generate new routes around temporarily unavailable nodes. Moving nodes have software routines that can request new neighbor searches automatically. This software, which is part of the Z-Wave stack, resides in on-chip memory.

Z-Wave Network Setup

Since Z-Wave devices do not possess unique network addresses (I.D. numbers) when purchased, there must be a procedure whereby the network's Static Update Controller (SUC) assigns I.D. numbers to devices being installed on the network. Z-Wave specifies that network installation should be accomplished either centrally using some kind of installer tool or locally using the devices themselves. However, as described in APPENDIX I — Z-Wave Usability Evaluation below, different Z-Wave device vendors have adopted different methods for achieving network installation locally.

Z-Wave Association Process

To support the creation of associations between buttons on a controller and actions of a controlled device, Z-Wave specifies that

- The network must provide an *Association Wizard*,
- There must be a *sanity check* of requested associations and
- All nodes must be able to present their supported capabilities.

Software routines to support these features, to the extent that product developers choose to develop and include them, further enlarge memory requirements.

Z-Wave Chips

Sigma Designs offers Z-Wave modules with 64K bytes of flash memory and provision for additional external memory. The earlier 3102 series modules have been replaced with the 4101 and 4102 series using a faster signaling rate. All modules have an integrated FSK radio and an 8051 processor core.

Z-Wave Application Development

To create devices that use Z-Wave networking, product developers typically use a C compiler to write application firmware for downloading into the flash memory on the chip. Sigma provides a collection of API (application programmer interface) routines in a Windows DLL (dynamically linked library) to help with this task.

Z-Wave Interoperability

To promote product interoperability between devices from different manufacturers, Z-Wave maintains a list of standardized command definitions and device class specifications. Z-Wave devices must pass a certification procedure costing $750 before they can display the Z-Wave logo.

Despite these measures, similar Z-Wave devices from different manufacturers have different behaviors, as described in some detail in APPENDIX I — Z-Wave Usability Evaluation below.

Z-Wave Device Types

Managing the routing of messages on a network is complicated, especially if some devices in the network are mobile. Z-Wave uses source routing, so any device capable of initiating communication must know which routes are currently possible, choose the best route and then embed the routing information into the messages that it sends. Such routing algorithms have been well developed for a variety of networks, but they require a lot of code. Lots of code means lots of memory on a chip and therefore higher build costs for devices that use the chip.

Z-Wave chips have 32K or 64K bytes of flash memory, with provision for adding more memory externally. To reserve as much memory as possible for the application code in a Z-Wave device, the Z-Wave communications stack must be kept as small as possible. Therefore, Z-Wave defines a number of different device types that have varying capabilities and stack sizes. The main Z-Wave device categories are *Controllers*, *Routing Slaves and Slaves*.

Z-Wave controllers can initiate communication with all nodes and so they have the largest stack. The master controller, called a SUC (static update controller), performs network management, distributes network topology information to secondary controllers and supports central or local device enrollment. Mobile controllers use a *portable controller stack* that allows devices to request rediscovery of moving nodes. There can also be a SIS (SUC I.D. server), which can automatically distribute network topology information to multiple controllers, but that software usually runs on a PC. Unless there is a SIS in the Z-Wave network, users have to manually copy network topology data from the master controller to any secondary controllers in the network whenever they add or remove Z-Wave devices.

Routing Slaves can initiate communication with a subset of nodes using a smaller Z-Wave stack. They depend on the SUC for network topology information.

Slaves have the smallest stack and can only respond to communications.

Z-Wave also defines *Installers* for doing centralized network setup and *Bridge* devices for connecting to other kinds of networks.

By defining devices with reduced-functionality in order to minimize cost, Z-Wave has given up the simplicity of peer-to-peer networking. This tradeoff is understandable in response to the complexity of routing, but because different devices have different capabilities, users have to know more about how the network functions. Perhaps the most restrictive issue for users is the requirement for a single master controller in a Z-Wave network.

INSTEON Compatibility with Z-Wave

INSTEON and Z-Wave radios are invisible to each other because they both use narrowband FSK radios but on different frequencies. The situation is similar to two different FM radio stations at different points on the radio dial. In the U.S., Z-Wave radios are tuned to 908.42 MHz while INSTEON uses 915.00 MHz.

In Europe Z-Wave uses 868.42 MHz and 921.42 MHz in Australia. INSTEON uses 869.85 MHz in Europe and 921.00 MHz in Australia, so there is no interference.

INSTEON and Z-Wave radios do not interfere with each other. This allows INSTEON and Z-Wave devices to co-exist in the same or neighboring networks and even to interact with appropriate interoperable network control devices.

INSTEON Compared with Z-Wave

The main differences between INSTEON and Z-Wave are that

- INSTEON is dual-mesh, Z-Wave is radio only;
- INSTEON propagates messages by simulcasting, Z-Wave routes messages;
- INSTEON uses backwards and forwards compatible Statelink commands, Z-Wave uses commands that must be understood by the responder;
- INSTEON devices are peers, Z-Wave has network controllers and slaves; and
- INSTEON requires no separate network enrollment step.

INSTEON Uses Both Powerline and Radio Communications

Radio communication is far from 100% reliable, as cell phone and WiFi users are frequently reminded from firsthand experience. Z-Wave's single media design is clearly sub-optimal to INSTEON's dual-mesh design. Z-Wave radios, because they use narrowband FSK (frequency shift keying) signaling, are considerably less sophisticated than cell phones or WiFi. Furthermore, because they share the unlicensed 900 MHz ISM (industrial, scientific and medical) band, they are required to transmit at low power. Metal in the home can block or reflect radio waves—installing radio wall switches in metal junction boxes can cause particular difficulties.

That is why INSTEON is dual-mesh—if radio fails, powerline provides a backup and vice-versa. In combination, two independently simple, low-cost signaling methods can be much more reliable than sophisticated, high-cost methods employed on single media with no backup.

Because it is radio-only, Z-Wave had to resort to complex network self-organization, self-healing and routing procedures in an attempt to maximize reliability. INSTEON, on the other hand, even though it employs the same sort of narrowband FSK radios in the 900 MHz range as Z-Wave, achieves greater overall reliability with far less complication, because it relies on dual-mesh powerline backup and repeated message simulcasting.

INSTEON Uses Simulcasting Instead of Routing

Simulcasting is much simpler than routing and more robust because multiple devices simulcasting the same message add to the signal power. For a complete discussion of how simulcasting works see *INSTEON, the Details*, available at www.insteon.com.

As explained above, routing entails complexity. Devices that initiate communication using a source routing algorithm, which is what Z-Wave uses, must know the topology of the network. Maintaining and distributing a network topology database is not trivial, especially with mobile devices. To keep costs down, Z-Wave has defined different classes of devices, some of which cannot participate in routing.

INSTEON is a Peer-to-Peer Network

INSTEON devices are two-way simulcasting repeaters[1], which means they all handle INSTEON messages in *exactly* the same way, with no need for network controllers or routers. A Z-Wave network, on the other hand, must contain a Static Update Controller (SUC) along with other kinds of devices, including slaves or routing slaves.

If you want more than one controller in your Z-Wave network and you don't have a SIS (SUC I.D. Server), you must choose a single controller as a master and use that controller alone for network maintenance. To set up your other controllers as secondaries you must go through an involved controller replication procedure. Thereafter, any time you add or delete network devices using your single master controller, you must repeat the entire controller replication process for all of your other controllers.

In contrast, INSTEON lets you add or remove INSTEON devices of any kind at any time, because no matter how a device appears to the user, to the INSTEON network all devices are peers. Therefore, setting up INSTEON devices requires far less customer knowledge and involvement.

INSTEON Requires No Network Enrollment

As a consequence of routing using network controllers, Z-Wave requires that new devices be enrolled in the Z-Wave network before controller buttons can be associated with device functions. Some Z-Wave vendors have found ways to hide the network enrollment step from users by combining it with the control association procedure, but others have elected to keep the two procedures separate. This situation is confusing if consumers have Z-Wave products from different vendors who have implemented different setup methods.

With INSTEON this problem doesn't arise because there is simply no need for network enrollment. There is no routing and there is no network controller. At the factory, INSTEON devices are each given a unique I.D. number that serves as a permanent network address. All INSTEON devices *automatically* become part of an INSTEON network and start simulcasting repeated messages as soon as a customer powers them up.

INSTEON versus Z-Wave Comparison Table

The following table summarizes the differences between INSTEON and Z-Wave.

Property	INSTEON	Z-Wave
Media	Powerline and radio	Radio only
Module types	All are peers	Controller Static controller (SUC) Slave Routing slave Enhanced slave Installer Bridge
Message propagation	Simulcasting repeaters[1]	Routing tables
Network topology	Full mesh	Routed mesh
RF interoperability	Yes, 915 MHz	Yes, 908.42 MHz
Command interoperability	Yes, Statelink	No, application and revision specific commands
RF data rate, bps	38400 instantaneous	9600 instantaneous
RF PHY	FSK in ISM Band	FSK in ISM Band
Powerline data rate, bps	13,165 instantaneous PL 2,880 sustained PL 1,440 standard msg payload 1,698 extended msg payload 1,034 user data	None
Powerline PHY	131.65 KHz carrier BPSK	None
X10 compatible[2]	Yes	N/A
Powerline phase bridging	RF or hardware	N/A
Acknowledged	Yes	Yes
Addressing	24-bit pre-assigned module I.D. (16,777,216 Devices)	32-bit home I.D. 8-bit node I.D. (232 devices per network)
Network enrollment	Automatic	Part of installation procedure
Groups	Databases in modules	Controller database
Commands	2-byte (65,536)	Command classes

Device types	3-byte (16,777,216)	Device classes
Global clock	Powerline zero crossing	No
Retries	Yes	Yes
Message length	15, 33 bytes	Variable
Collision avoidance	Yes	Yes
Triac control	Yes	Yes
SRAM	256 bytes	2048 bytes
Flash	4K x 14 bits (7K bytes)	32K bytes
EEPROM external	4K bytes	Up to 24K bytes
EEPROM internal	256 bytes	0
Watchdog	Yes	Yes

WiFi

In recent years, WiFi (IEEE 802.11) has become the de facto standard for broadband networking of wireless LANs (local area networks) in the home, in offices and at an increasing number of commercial 'hotspots' around the world.

About WiFi

Most laptop computers and network routers now come with WiFi 802.11n built-in. WiFi is the clear industry leader for broadband, wireless networking in the home. WiFi is well suited for sharing files, streaming video and other data intensive applications.

IEEE 802.11, the standard underlying WiFi, actually comes in several different version, a, b, g and n. 802.11a is for licensed operation in the 5 GHz band and is mainly used by businesses. 802.11b, g and n are the WiFi versions that power most wireless networks. Version b, capable of communicating at 11 Mbps (megabits per second), appeared on the market in 1999, followed by version g at 54 Mbps in 2002. Version n, at 100 Mbps or more, began shipping in 2006.

WiFi version	Peak data rate	Radio band
802.11a	54 Mbps	5 GHz
802.11b	11 Mbps	2.4 GHz
802.11g	54 Mbps	2.4 GHz
802.11n	100 Mbps minimum	2.4 GHz

WiFi is typically implemented in a star networking topology—not a mesh, meaning that all signals are fundamentally point-to-point.

Upon power up, WiFi networks need to run through a configuration process which is time consuming even for a small home LAN with only a few devices. For a larger application (hundreds), this process would take an unknown amount of time during which certain communications would not yet be possible.

The typical range for a WiFi radio inside the home is 50 meters or up to 100 meters unobstructed line-of-sight. WiFi is fairly power hungry, typically with receivers always on. The number of nodes per WiFi LAN is limited to 32 and each node will need up to one megabyte of system resources plus a moderately powerful microprocessor to run the WiFi software. By using technology like PBCC (packet binary convolutional coding), CCK (complementary code keying) and DBPSK (differential binary phase shift keying), WiFi achieves impressive performance and reliability, but not without significant cost.

TCP/IP

To form network connections and transport data, WiFi uses the same protocol as the Internet, TCP/IP.

For remotely connecting computers together, TCP/IP is used literally all over the world. TCP/IP ships data over all kinds of networks, from the smallest home office WiFi LAN to the global Internet. It is so ubiquitous that people use it more and more for VOIP (Voice Over IP) telephone and IPTV television service.

TCP/IP is really two standards, TCP (for Transmission Control Protocol) and IP (for Internet Protocol). IP transports a block of information called a *datagram* from point A to point B by handling two basic functions, addressing and fragmentation. A header in the datagram carries an address field that network routers use to select a path for transmission to the ultimate destination. Other fields in the header are used to fragment and reassemble datagrams when necessary to get them through 'small packet' bottlenecks. Packets can be labeled with a *Type of Service* for traffic prioritization and there are other options for security and routing restrictions. Datagrams can theoretically contain up to 65,536 bytes, but in practice they are limited to 576 bytes or 64 bytes of header and 512 bytes of data.

IP handles each datagram independently from any other, without any logical connections, virtual circuits or guarantee of delivery. TCP makes up for these shortcomings by providing reliable, streaming connections. Streaming hides the underlying datagrams and makes data look like a sequence of bytes, much like a file. Reliability comes from retransmission if data becomes lost. TCP also handles network adaptation and flow control to maximize throughput without overloading the network.

Anyone who uses the Internet knows that this technology works superbly well. Why not use it, then, to connect *everything?* Shouldn't light switches have IP addresses? The answer is that yes, they should, but the light switch itself should not be networked using TCP/IP or else the light switch would have to be built like a PC or smartphone. TCP/IP is *complicated*. A minimal implementation that can run on a medium-performance microprocessor such as an ARM7 requires 2K of RAM and 14K of code memory—and this does not take into account any application-level software or the modem hardware and firmware to connect to the physical communication media. Light switches of such cost and complexity cannot compete in the mass marketplace.

Furthermore, TCP/IP is not architected for dense networks of dozens or hundreds of devices, with each device requiring only a few bytes of payload in a message. Despite simplification efforts such as OSIAN from the University of California at Berkeley and 6LoWPAN from the IETF (Internet Engineering Task Force), devices using these stripped-down protocols have not appeared in the marketplace.

It is not necessary for dense clusters of sensors and controllers to themselves use TCP/IP. We can still have the best of both worlds. The solution is to add a gateway device to your INSTEON network. The gateway device could be a PC connected to an INSTEON bridge device like the INSTEON PLM (Powerline Modem) or it could be a lower-cost dedicated controller. The gateway only needs sufficient resources to run home management software that can control devices on your INSTEON network via an Internet or LAN TCP/IP interface.

INSTEON devices can appear as if they are on the Internet or part of a LAN, using any one of dozens of home management software applications.

INSTEON Compared with WiFi

Using WiFi to network together low-cost devices like light switches is theoretically possible, but WiFi is overkill by a wide margin. The *slowest* WiFi specification, 802.15b, delivers data at 11 megabits per second, far in excess of what a light switch needs to dim a light or a thermostat needs to control a heater. TCP/IP transport, arguably the gold standard for packet routing, requires a *minimum* of 30 bytes of overhead per packet, with 2K of RAM buffers and at least 14K of code space just for the software stack.

Proposed reduced-overhead and lower-power variations of IP signaling, such as 6LoWPAN and OSIAN, are still over-complex for dense command and control and they have yet to be proven by adoption in the marketplace.

WiFi radios work very well, but they are complicated and so power-hungry that the only way to implement battery-operated devices is with rechargeable batteries and frequent recharging. Advanced as it is, WiFi nevertheless has no powerline backup. As with other single-media networks, if communication fails for any reason, the only recourse with WiFi is to retry.

In contrast, INSTEON's data rate is optimized for home control. It is fast enough that users don't experience a noticeable delay when controlling devices, but not so fast that simulcast messages might jam each other. And simulcasting is how INSTEON avoids routing altogether. All INSTEON devices within range repeat[1] identical messages at precisely the same time, with each device adding to the strength of the signal, so simulcasting is not only radically simpler than routing, it is more robust. Simplicity translates into low-cost—the INSTEON engine for communicating both by powerline and radio occupies a mere 2600 bytes, with an entire application like a lamp dimmer residing in only 7K bytes, all running in a low-end microcontroller such as the PIC16f638.

Perhaps the strongest argument against increasing the cost of devices by building WiFi into them is that you can get the same benefit but without incurring the cost in every device. With a single gateway between a WiFi network and INSTEON, all of the devices on an INSTEON network can still appear as part of the WiFi network. WiFi is great at networking together computers, broadband access points, printers and other high-performance gear. With an INSTEON gateway on the WiFi network, everything else in your home can join the LAN and appear on the Internet without costing a second mortgage.

Bluetooth

Bluetooth radio, defined by the Bluetooth SIG (special interest group, www.bluetooth.org) and standardized as IEEE 802.15.1, is a wireless ad-hoc point-to-point personal area networking (PAN) technology.

About Bluetooth

Designed for low power, but limited to a 10-meter range, Bluetooth radio is mostly used in wireless headsets for cell phones, automotive hands-free applications and for PDA and PC cable replacement.

Bluetooth radios operate in the 2.4 GHz band, using frequency hopping spread spectrum (FHSS) to achieve a peak data rate of up to 3 Mbps (megabits per second). A Bluetooth PAN (personal area network) supports only seven nodes, yet the Bluetooth software stack can occupy up to 250 Kilobytes of system resources.

INSTEON Compared with Bluetooth

Bluetooth, because it was designed for personal connectivity, is much faster and more complex than needed for home control applications. Considering Bluetooth's cost, limited range, point-to-point topology (not a mesh) and lack of powerline backup, INSTEON is a superior choice for networking together mass-market devices like light switches.

Bluetooth coexists with INSTEON without any issues, because Bluetooth occupies the 2.4 GHz band and INSTEON radio uses 915 MHz.

LonWorks

LonWorks is a networking technology developed in 1988 by Echelon, Inc., (www.echelon.com), a public company (NASDAQ: ELON) headquartered in San Jose, California. LonWorks is mostly deployed in building and factory automation, commercial control and meter reading applications.

About LonWorks

LonWorks is a sophisticated, high-performance routed network that uses special loop-free (learning) routers and repeaters to reliably deliver messages. The LonWorks stack implements the full seven-layer OSI (Open Systems Interconnection) model. At the PHY (physical) layer, LonWorks can talk over twisted pair, coax, fiber optics, powerline, infrared and radio, with the majority of actual installations using dedicated twisted pair wiring.

OSI layer	Layer name	LonWorks software services
1	Physical	TP, CX, FO, PL, IR, RF
2	Link	MAC: predictive CSMA, CA; Optional CD, priority
3	Network	Connectionless, domain-wide broadcast, loop-free, available learning routers
4	Transport	ACK/NAK multicast, unicast, authentication server; transaction control (ordering, duplicate detection)
5	Session	Sets up, coordinates, terminates application communication
6	Presentation	Syntax conversion
7	Application	QoS, authentication, privacy

The LonWorks platform, intended as a BACnet (Building Automation Control network) replacement, uses a protocol called *LonTalk*, formalized as ANSI/CEA 709.1 and IEEE 1473-L standards. LonTalk packets can contain a large amount of information, as shown in the table below.

Field	Bytes
Link header	1
Address information	4
Service type	1
Session header	2
Presentation header	2
Data	2 to 218
CRC	2

Echelon offers *Neuron* chips to manufacturers for creating products, but the cost of the chips (under $10) would have to be substantially lower to permit mass-market consumer devices in the home.

For product developers, Echelon offers a number of tools and development kits. Programming of Neuron chips is done in *Neuron C*.

INSTEON Compared with LonWorks

INSTEON is optimized for home control, while LonWorks has found applications mostly in commercial and industrial settings. LonWorks is reliable, fast and flexible, but this sophistication comes at a price. Although LonWorks has been around since 1988, its price-performance point has so far proven to be too high for widespread adoption in the consumer home control market.

INSTEON, on the other hand, has been architected from the ground up to meet consumer expectations for simplicity, affordability and reliability. Because it is a modern design, INSTEON is not bound with any legacy issues, but instead can take advantage of the most recent advances in technology. In the near-term at least, INSTEON and LonWorks networks will likely remain in different market segments, although they could be interconnected with appropriate internetworking devices if a marketplace demand emerges.

HomePlug

The HomePlug Powerline Alliance (www.homeplug.org) has released two standards for high-speed, broadband information transport over the powerline and another standard, Green PHY, for lower-bandwidth (3.8 Mbps) powerline signaling.

About HomePlug

HomePlug 1.0, based on Intellon *PowerPacket* technology, can transport data over the powerline at a bitrate of 14 Mbps (megabits per second). Using state-of-the-art techniques, this protocol demonstrates that the powerline is capable of supporting high-performance broadband networking. Consumers, however, have adopted WiFi radio (IEEE 802.11) much more enthusiastically for wireless computer networking, with WiFi already being used in 80% of U.S. homes. The current WiFi standard, 802.11n, operates at a minimum speed of 100 Mbps.

HomePlug AV, which is even more advanced with a raw data rate of 200 Mbps, is capable of transporting multimedia and HDTV streams over the powerline. Despite successful demonstrations of the technology, it is too early to tell if HomePlug AV will be widely adopted by consumers or if a radio technology such as WiFi will find greater acceptance.

Green PHY is a “certification profile” of IEEE 1901, which is a form of 802.2 IP (Internet Protocol) networking, running at 3.8 Mbps (million bits-per-second), with a minimum throughput of 1 Mbps. The 690-page specification is available at a cost of $99. Although it is significantly less expensive that HomePlug AV, Green PHY is still much more complex than required for basic sensing and control. It was designed by a committee for use in the smart grid, especially including electric meters. Fully routed, it is not optimal for dense networks consisting of dozens to hundreds of nodes. Lacking wireless backup, powerline-only communications can suffer impairments that only repeated retries can hope to overcome. HomePlug's single media design is clearly sub-optimal to INSTEON’s dual-mesh design. Industry participants have come to recognize this fact. As such efforts are underway to resolve this deficiency by bridging to a wireless technology. These efforts will clearly lead to networking inefficiencies, additional hardware requirements and added costs.

Companies who wish to contribute intellectual property to HomePlug’s powerline specifications must be *Participant Members* in the HomePlug Powerline Alliance, at a cost of $15,000 per year ($9,500 for the first year). Access to the specifications requires *Adopter Membership* for $5,000 annually ($3,500 for the first year).

INSTEON Compared with HomePlug

INSTEON is a home command and control network, while HomePlug AV uses the powerline for advanced computer networking and media transport, so there is no overlap in the marketplace. On the powerline itself, the two signals do not interfere with each other, so there is no problem with coexistence.

HomePlug’s Green PHY initiative has resulted in a chip from Qualcomm Atheros, the QCA7000, announced in December 2011. It is too early to tell what influence a new proposed single mesh powerline standard will have in the marketplace of the future.

Intellon

Acquired by Atheros (www.atheros.com) in September 2009, Intellon, of Ocala, Florida, got its start in 1989 by developing the winning designs for adoption as the CEBus powerline and RF signaling standards. Although CEBus did not find acceptance in the marketplace, Intellon went on to improve its spread spectrum technology to the point where over a hundred megabits per second could be transported reliably over the powerline.

About Intellon Technology

Intellon's broadband technology, called *PowerPacket*, is at the heart of the HomePlug 1.0 broadband powerline networking specification. As a founding sponsor and member of the board of directors of the HomePlug Powerline Alliance, Intellon is a primary driver of the even-more-advanced HomePlug AV technology.

As one might expect, PowerPacket is very sophisticated and complex to be able to transport so much data reliably in such a hostile environment.

At the physical (PHY) level, PowerPacket uses multiple carrier OFDM (orthogonal frequency division multiplexing, also used by WiFi and DSL), with interleaving and both Viterbi and Reed-Solomon forward error correction (FEC). The control software dynamically negotiates an optimum payload data rate by choosing carriers, switching between DQPSK and DBPSK modulation and varying the FEC rate. The signal is spread from 4.5 MHz to 21 MHz on the powerline, with a digitally filtered PSD (power spectral density) to match HomePlug's requirements.

The media access control (MAC) layer uses CSMA (carrier sense multiple access) with a randomized contention window and exponential back off, like Ethernet. Other MAC services include priority resolution, ACK/NAK (acknowledgements), ARQ (automatic repeat requests), segmentation of slow frames for QoS (quality of service) and 56-bit DES (digital encryption standard) encryption using cipher block chaining.

This technology is clearly a *tour de force*. Highly advanced, it is well suited for its intended broadband applications, but it is far too expensive to find its way into devices like light switches.

INSTEON Compared with Intellon Technology

Intellon's broadband technology does not compete with INSTEON as explained above. Intellon does still offer legacy CEBus-inspired SSC (spread spectrum carrier) chips, but the marketplace has not adopted CEBus for reasons explained in the following section, so the chips are mainly used in proprietary building automation and vehicle brake control systems. Consequently, INSTEON does not overlap Intellon's technology in the marketplace, although both signals can coexist on the powerline without interference.

CEBus

In 1984, the EIA (Electronic Industries Association, now called CEA, for Consumer Electronics Association) formed a Technical Steering Committee to develop an ambitious standard for interconnection of all kinds of devices in the home. Called CEBus, for Consumer Electronics Bus, this comprehensive effort strove to unify communications over coax, twisted pair, powerline, radio, infrared, audio/video and fiber optic media with a command language called CAL (Common Application Language).

About CEBus

The CEBus committee formed working groups for each of the seven different media and the working groups then conducted competitions among industry proponents to demonstrate technologies for adoption as signaling standards on the media. Intellon won the competition for powerline and radio with a spread spectrum technology that was very innovative for the time.

On the powerline, the Intellon technology used a custom designed “chirp” signal that occupied spectrum between 100 KHz and 400 KHz. Virtually the same idea was adopted for radio, but spread about a carrier in the unlicensed 900 MHz ISM (industrial, scientific and medical) band.

After the working group “bakeoffs,” the EIA membership ratified the CEBus standard as EIA-600 in 1994 and published it as a stack of documents almost a foot high.

Although Intellon did offer chips implementing the powerline and radio parts of the standards, devices built with them were complex and expensive. One dimmer switch used eleven integrated circuits on two circuit boards, far too complex and expensive to meet mass-market consumer needs.

Major industry players did not embrace CEBus, so it never gathered the momentum necessary to become adopted in the marketplace. Over-complexity and over-reaching by the committee of engineers were likely reasons for its demise, but timing was probably another, since the Internet was virtually unknown in those days and relatively few homes had PCs.

INSTEON Compared with CEBus

Much has happened since CEBus failed to gain traction in the mid-1990s. Most U.S. homes have computers, most of those are connected to the Internet and a large number are wirelessly networked using WiFi. With cell phones, satellites, DSL and broadband cable, much of what CEBus set about interconnecting is now interconnected by other means. Nevertheless, it is still true that infrastructure devices like light switches, security sensors, clocks and door locks have yet to be networked. The failure of CEBus to achieve that goal underscores the importance of simplicity and affordability in a consumer environment.

UHF

UHF or ultra-high frequency is shorthand for numerous proprietary radio signaling methods that use the 260 to 470 MHz band.

About UHF

There is a lot of equipment in the world that use radio for signaling. Most of these legacy applications communicate using the UHF band, with 433 MHz being a popular frequency. Applications include:

- Security systems
- Lighting controllers (Lutron, for example)
- Remote keyless entry for cars
- Garage door openers

To qualify for unlicensed operation, the FCC requires these devices to operate only intermittently and at low power, which results in a range typically limited to a few tens of meters.

Developed independently over many years by different manufacturers, these systems use differing modulation schemes and data encoding methods, with no truly open standards or interoperability.

INSTEON Compared with UHF

In contrast to the myriad of proprietary UHF signaling protocols, INSTEON is an open networking standard, requiring only that products be INSTEON-certified to ensure interoperability. There is no interference between INSTEON and UHF devices because they operate at different frequencies. However, by migrating to the INSTEON standard, products that currently use UHF would be able to interact with all kinds of other INSTEON-networked devices—and the more nodes on a network, the more benefits it can bring to users.

UPB

UPB (Universal Powerline Bus) is a low-speed powerline-only network designed by PCS (Powerline Control Systems, Inc., www.pcslighting.com), of Northridge, California.

UPB devices send messages over the powerline by coding data in the timing of high amplitude pulses. Normal UPB devices like light switches do not repeat or amplify messages sent by other UPB devices, so all of the signal power must come from the UPB transmitting device. Because UPB only communicates via the powerline, if for any reason powerline messaging fails, UPB devices can only retry and hope for the best. Unfortunately, electrical noise from many types of lamp dimmers and other electrical equipment can easily masquerade as a UPB signal pulse, causing interference that can last indefinitely. For a case study in UPB noise immunity contact INSTEON.

INSTEON, on the other hand, is a *dual-mesh* network, using both radio and powerline to back each other up. Moreover, INSTEON devices repeat[1] each other's messages by *simulcasting* them in precise timeslots synchronized to the powerline zero crossings. With each new device adding to the signal strength, an INSTEON network grows in reliability as more devices are added.

There is no integrated UPB chip available. Instead, the UPB protocol is implemented on general-purpose microcontrollers with discrete external components. Product development entails writing application code that runs on the microcontroller.

PCS has two U.S. patents issued. Number 6,734,784, granted May 11, 2004, is titled *Zero Crossing Based Powerline Pulse Position Modulated Communication System*. Number 6,784,790, granted August 31, 2004, is titled *Synchronization/ Reference Pulse-Based Powerline Pulse Position Modulated Communication System*.

INSTEON Compared with UPB

The most notable differences between INSTEON and UPB are that

- INSTEON is dual band, UPB is powerline only;
- INSTEON repeats[1] messages by simulcasting, UPB does not repeat messages making it point-to-point;
- INSTEON cannot be jammed by triac transients; and
- INSTEON device setup does not require special tools.

X10

At the low end, X10 powerline signaling technology has been around since the 1970s, but its early adoption is its limiting factor—it is too unreliable and inflexible to be useful today as an infrastructure home-control network. Although the X-10 Ltd. company and factory are no longer in business, there are still numerous legacy devices still in use.

How X10 Works

Invented in Scotland by Pico Electronics in 1975, X10 was a pioneering breakthrough for its time, but even though it employed one of the world's first custom integrated circuits, the technology of the 1970s put severe constraints on its design.

For example, there can only be 256 different X10 devices on a single powerline, because each X10 device can only be assigned one of 16 possible House Codes (A through P) and one of 16 possible Unit Codes (1 through 16).

Furthermore, X10 defines only 16 different Command Codes, but not all devices can respond to all X10 commands. The six most common X10 commands are *On*, *Off*, *Dim*, *Bright*, *All Units Off* and *All Lights On*.

X10 transmits one bit of information at each powerline zero crossing (every 8.33 milliseconds). A simple command-plus-address message contains 100 bits and takes 833 milliseconds to send (8/10 of a second).

A one-millisecond burst of 120 KHz carrier signifies a *one* bit and the absence of a carrier signifies a *zero* bit. An X10 message consists of a 4-bit **Start Code** followed by an 8-bit **House Code** followed by a 10-bit **Key Code**. Each message is sent twice, followed by 6 zero-crossings of silence before starting another message. (The silence interval can be omitted if certain X10 Commands, such as *Bright* or *Dim*, are being repeated.)

INSTEON Compared with X10

Developed as it was in the 1970s, X10 is too limited to function as a command and control infrastructure network in the mass market. Not only is X10 powerline signaling dreadfully slow, but X10 communication has no built-in mechanism to verify that X10 messages got through—X10 is open loop. Although X10 did eventually define Status Request and Status Response Commands, very few X10 devices actually employ them and those that do take even more time to send and receive the extra messages.

Installing more than a few X10 devices in a network is not for the faint of heart. It usually requires blocking couplers, repeaters and filters—and then is highly likely to function properly for just a short while. X10 is fundamentally subject to false positives, both because of its signaling design but also of its limited addressing schema. Many X10 customers have lived through a neighbor inadvertently controlling products in their homes.

INSTEON Uses Both Powerline and Radio Communications

Because INSTEON powerline messages are repeated using radio and radio messages are repeated on the powerline, INSTEON messaging is highly reliable while still using simple signaling methods on both the powerline and the radio. Dual-band products also naturally couple the electrical phases without the need for additional products.

INSTEON Devices are Simulcasting Repeaters

Because INSTEON devices simultaneously repeat[1] each other's messages, adding more devices to an INSTEON network adds more energy to the INSTEON signal. Thus, as an INSTEON network grows it becomes more reliable, while adding X10 devices weakens an X10 network.

INSTEON is Closed Loop

All INSTEON devices can both listen and talk and the INSTEON protocol requires that all INSTEON messages that are not broadcast be acknowledged.

INSTEON is Faster than X10

At each powerline zero crossing (every 8.33 milliseconds), INSTEON sends 24-bits of information, while X10 sends only ½ bit. Thus INSTEON's raw signaling rate is faster than X10's by a factor of 48.

INSTEON Has a Large Address and Command Space

With room for more than 16 million addresses and 65 thousand basic commands, INSTEON is clearly in a different league compared to X10 with only 256 addresses and 16 commands.

Conclusions

INSTEON is fundamentally more reliable than single-band technologies.

INSTEON is fundamentally more interoperable than other technologies because of Statelink.

INSTEON is brilliantly simple:

- INSTEON uses both existing house wiring *and* the airwaves to carry messages, so each signaling method can be kept very basic because they back each other up.
- INSTEON repeats messages by simulcasting, with each new device adding more energy to the INSTEON signal, so an INSTEON network becomes more robust and reliable as more devices are added.
- INSTEON products are backwards- and forwards-compatible due to Statelink.
- INSTEON is optimized for command and control, with firmware that runs on the smallest microcontrollers.
- INSTEON devices can be built in high volume at the lowest-possible cost.

Although INSTEON is simple, simplicity is not a limiting factor, because INSTEON bridge devices can connect to all kinds of outside resources like computers, smartphones, the Internet and other networks in the home whenever needed. Networks of INSTEON devices can evolve as the marketplace does.

Most other networking schemes are far more complicated than INSTEON, but without significant compensating benefits in command and control applications. This is understandable, because none of them are dual-mesh and most of them are routed, so they had to trade cost and complexity for reliability and performance. The highest-performance networks, like WiFi, Bluetooth and HomePlug, do not compete with INSTEON because they are intended for different purposes, such as computer networking, media streaming or cable replacement.

“Everything should be made as simple as possible, but not simpler.”

Albert Einstein (1879-1955)

NOTES

1. Battery-operated INSTEON RF devices, such as security sensors and handheld remote controls, must conserve power. Accordingly, they are normally configured to not retransmit INSTEON messages from other INSTEON devices. Such devices can nevertheless both transmit and receive INSTEON messages, in order to allow software setup and diagnostic procedures and to ensure network reliability.

2. At a minimum, X10 compatibility means that INSTEON and X10 signals can coexist with each other on the powerline without mutual interference. INSTEON-only powerline devices do not retransmit or amplify X10 signals. But X10 compatibility also means that designers are free to create hybrid INSTEON/X10 devices that operate equally well in both environments. By purchasing such hybrid devices, current users of legacy X10 products can easily upgrade to INSTEON without making their X10 investment obsolete.

APPENDIX I — Z-Wave Usability Evaluation

To gauge the user experience with Z-Wave devices, SmartLabs evaluated a small Z-Wave system consisting of the following products:

#	Mfr	Product	Model number	Form factor	Powered by	Features
1	HomePro	Remote control	ZTH100	Handheld	2 AA cells	12 x 2 text LCD
2	HomePro	Lamp module	ZDP100	Plug-in	110 VAC	Dimmer
1	Intermatic	Remote control	HA07	Desktop	4 AA cells	Custom LCD
2	Intermatic	Lamp module	HA03	Plug-in	110 VAC	Dimmer
1	Intermatic	Indoor appliance module	HA02	Plug-in	110 VAC	Relay switch
1	Intermatic	Outdoor appliance module	HA04	Plug-in	110 VAC	Relay switch

We plugged the products into outlet strips on a tabletop, so we did not test the range and reliability of the Z-Wave signal. By combining products from two different manufacturers, HomePro and Intermatic, we checked the ability of Z-Wave certified devices to interoperate. The results fell into four categories:

1. Z-Wave Network Setup
2. Z-Wave User Interfaces
3. Missing Z-Wave Modules
4. Z-Wave Lamp Dimming

Z-Wave Network Setup

Z-Wave Allows Only One Master Controller

Because Z-Wave is a routed network, new Z-Wave devices must be enrolled into the network before they can be used. You can only have one *master controller* in your Z-Wave network, because the master controller maintains the database that represents the network's topology.

Whichever device you choose as your master controller, to add *secondary controllers* to your Z-Wave network, you must go through a multistep controller replication process. The upshot is that only your master controller can add or remove Z-Wave devices from your network, so any time you modify your network you have to repeat the controller replication procedure in order to copy the new master controller network topology database to all of your secondary controllers.

Z-Wave Network Enrollment and Button Associations

After you add a new Z-Wave device to your network by enrolling it with your master controller, there still has to be a choice of which button or buttons on the master controller will operate the device. In other words, there are two issues to resolve when adding a new Z-Wave device to your Z-Wave network—network enrollment and button association.

The two different controllers that we evaluated use two very different methods for accomplishing these two tasks. The Intermatic controller requires two distinct steps—first you enroll a new device into the Z-Wave network, then you associate buttons to control the device. We had to refer to the Intermatic instruction manual to find out how to perform these steps, because the controller's buttons do not have obvious labels for performing this setup and the display cannot show arbitrary text prompts.

In contrast, the HomePro handheld controller merges the two setup steps into one by using the concept of HomePro *groups* and HomePro *scenes*. There are six numbered buttons on the HomePro handset, with each button able to control a HomePro group or scene. The difference between a group and a scene is that scenes can remember brightness settings.

To add a new Z-Wave device to the HomePro master controller, you traverse a text menu tree and follow text prompts on the display. The controller's software can recognize whether a device is new to the network or if it is already enrolled in the network and just being associated with more than one HomePro group button. The software automatically enrolls devices that are new to the network without involving the user, so users believe they are simply performing button associations.

Difficulty Enrolling Previously Enrolled Z-Wave Devices

At first try we were unable to enroll the Intermatic devices using the HomePro handset as the master controller. The reason turned out to be that the Intermatic devices had been previously enrolled using the Intermatic controller as the master. It was not clear from the instruction manual what to do, but we found a menu screen on the HomePro handset that allowed us to reset the Intermatic devices. After resetting we succeeded in getting the Intermatic devices to work with the HomePro handset.

Aware of the problem, we found that when using the Intermatic controller as the master, we could similarly reset devices before enrolling them by following a procedure in the instruction manual.

Issues When Replicating the Master Controller

While we had the Intermatic controller set up as the master, we tested the procedure for replicating it into the HomePro handset as a secondary controller. This required studying the instruction manuals for both controllers and we had trouble with steps timing out before we could complete them. Eventually we succeeded in setting up the HomePro handset so that it contained the network enrollment information, but the button associations did not transfer over even though we selected that option. We therefore had to manually set up new button associations on the Home Pro handset.

Device Location Issues

Our test setup was on a tabletop, so range was not an issue. However, the instruction manual recommended that if we moved a device from one location to another, we should un-enroll it from the Z-Wave network then re-enroll it at the new location. Presumably, this would force the master controller to adjust its network topology database so that routing would be optimized, but the re-installation of a device can be a chore, especially if you forgot how to do it and have to appeal to the instruction manuals.

Another issue that concerned us was enrolling devices far away from the master controller. Z-Wave optionally allows for a controller's radio transmissions to be at low power during network enrollment for security reasons. If a manufacturer enabled this feature, how would you get a Z-Wave device that was not close to the master controller to join the network? Even at normal transmission power levels, how would a master controller know how to route messages to an un-enrolled device that is so far away that intermediate routing slaves would be needed to reach the new device? Unless Z-Wave has provided software to handle these conditions, it would seem that a device would have to be kept near to the master controller for initial enrollment and this could be a problem with wired-in devices like light switches.

Z-Wave User Interfaces

Button Pairs versus On/Off Toggles

The Intermatic controller uses on/off button pairs to control devices, while the HomePro handset uses single buttons that alternate between on/bright and off/dim. Neither controller is “guest friendly,” meaning that a person who had never seen one before would not be able to figure out how to use it without some trial and error.

LCD Displays

Both devices have an LCD display, but the Intermatic display has fixed icons and text messages along with a “union jack” text area of only six characters, as opposed to the 12 character by two-line text display of the HomePro handset. Neither display has a backlight, so they cannot be read in the dark. The Intermatic display is always on, but the HomePro display turns off entirely after you have not pushed a button for several seconds. Pushing any button turns the HomePro display back on, but then you wonder: did the button you pushed only turn on the display or did it also perform the button’s function?

Button Labeling

The Intermatic controller has a hinged cover that hides buttons that you use to perform setup functions. It is not obvious that the cover can be opened, but inside the cover there is space for writing labels for the buttons. When the cover is closed there are six on/off button pairs labeled with numbers, but there is also a *shift key* that causes the buttons to control an additional six groups of devices. There is a small icon on the display that indicates the shift state, but unless you check it before you press a button, you might be controlling the wrong set of six devices.

On the HomePro handset, it is not clear from the button labels what they do. The group toggle buttons are labeled with a single digit, with no provision for writing a descriptive label. To control a HomePro scene, you first have to press a button labeled *S*, but this is far from obvious. Digit buttons alternate between turning groups of devices on and off, but for scenes you have to program one button to turn the scene on and another button to turn the scene off.

The HomePro remote has buttons with icons for *all on* and *all off*, but it is not obvious what they will do unless you already know. There is a menu system, but the only way to navigate it is by trial and error, because there is no indication that there are submenus or additional choices in the current menu. It is easy to get into the menu system inadvertently without knowing how to get out.

Keypress Responses

Keypresses on the HomePro remote are erratically de-bounced. For example, pressing the *OK* button once can answer *OK* to *two* menu prompts so quickly that the first menu prompt cannot be read.

The HomePro handset locked up once after multiple presses of the *1* button, displaying *Dimming Group 1*. We had to remove the batteries to reset the unit and then we had to reset the time.

User Feedback

Both controllers give feedback when a Z-Wave message is sent successfully, but there is no indication as to what the state of the device you are controlling actually ended up being. For example, you can brighten or dim lights by holding down a button for a variable length of time, but unless you can see the light that you are controlling, you will not know how bright it got when you let up on the button.

You can turn lights on and off rapidly using the HomePro handset, but if you try this with the Intermatic controller, the commands may not get through, even though the display shows the *Successful* text icon.

Missing Z-Wave Modules

Communication Retries Lock Up the Controller

There is a severe problem when controlled devices are removed from the Z-Wave network without going through the network un-enrollment procedure. In that case Z-Wave controllers will keep trying to send commands to the missing devices for several seconds. During the retry time, both the Intermatic and the HomePro controllers ignore button presses, so you are locked out from doing anything else.

There are several reasons that a Z-Wave slave device might be removed from the Z-Wave network without un-enrolling it. One is that the device might simply have stopped working. Another might be that you have some Z-Wave devices that control your Christmas lights, but when you remove the lights and unplug the devices after Christmas, you don't remember that you are supposed to go through the un-enrollment procedure. A third possibility is that you've installed a lamp module on a switched outlet and somebody has turned the switch off, so the lamp module is not powered up.

To test the effect of missing modules, we enrolled three modules as a group using the Intermatic controller as the master. With the first module unplugged, the Intermatic controller would control the first one, retry the second one without success for seven seconds, then control the third one and finally illuminate a *Not Successful* Message. The Intermatic controller would not respond to button presses during the entire seven seconds. When we set up the HomePro handset as a secondary controller to the Intermatic master, the HomePro handset controlled the two modules that were present right away, but then the handset ignored button presses for five seconds until the LCD displayed a *Group Failed!* message. When we set up the HomePro handset as the master controller, the lockup period was shortened to just under two seconds.

No Way to Un-enroll Lost or Broken Devices

If the HomePro handset is your master controller, there is no way to un-enroll a previously enrolled device without pushing a button on the device. Clearly, if the device stops working, you have a problem, because there is no button to push. The only remedy is to factory reset the entire HomePro controller, wiping out all of your network enrollment and other setup information and then to manually re-enroll every device in your Z-Wave network.

Z-Wave Lamp Dimming

The lamp dimmers from Intermatic and HomePro do not dim lights the same way. Both the Intermatic and HomePro dimmers come preprogrammed with different ramp rates (the time it takes to dim or brighten a lamp all the way) and neither ramp rate is adjustable by the user. HomePro modules dim or brighten first, followed by Intermatic. Neither module dims to full off.

When you use the Intermatic controller to dim lights manually by holding down an *off* button, HomePro modules first go to full brightness before they start dimming, but Intermatic modules start dimming from whatever their current brightness is. With mixed devices like this, if you had set the lights to a dim level you liked and then tried to dim the lights further, you would get a surprise when the HomePro modules suddenly went full on before dimming.

If you use the HomePro handset to manually dim both the Intermatic and HomePro modules to a certain level, then turn them off with a quick button push, another quick button push turns the Intermatic modules full on, but the HomePro modules go to the last level you dimmed to. Trying to fix this by manual dimming doesn't work because the modules have different ramp rates.

The HomePro modules we tested dimmed somewhat erratically, especially when operated with the Intermatic controller. The light sometimes "flashed" at the end of dimming when we let up on the controlling button.

While it is true that Z-Wave devices from Intermatic and HomePro do 'interoperate' in the sense that both controllers can activate both kinds of dimmers, the actual behavior of the lights is not the same. For consistent performance, consumers would have to purchase all Intermatic or all HomePro devices.