Wireless Motion Control
The Next Evolution in Motion Networking

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Summary

In the continuing evolution of motion control networks, the world has seen a movement from the traditionally cabled analog-based motion wiring to more advanced fieldbus solutions such as CANopen and DeviceNet to high-performance Ethernet-based motion networks being deployed today. In hindsight this evolution makes sense. As processor technology improved and network infrastructure grew solutions presented themselves to the problems of configuring cumbersome and expensive cabled applications. This has yielded several powerful Ethernet-based networks capable of meeting the high-performance motion needs of many applications. Without a doubt each of these networks offers advantages in their own right. However, none offers a complete solution to the cabling problem that continues to account for significant percentages of machine cost and real estate. In addition, Ethernet-based motion networks are all fighting to claim performance advantages while ignoring the fact that for a vast majority of applications they are simply over designed.

Wireless motion control offers a safe, robust and cost effective alternative to control multi-axis motion control applications without the need for control cables or cable tracks and housing. In addition, wireless control as presented here solves a majority of applications where an Ethernet network is simply too expensive for the job. This paper examines the value benefits of a wireless approach and addresses the most obvious concerns of safety, reliability and latency.

The Simplest Choice

Wireless Landscape

When considering a core technology on which to base wireless motion control, it is obvious that many options are currently available. The primary list includes: Wi-Fi 802.11.x, Bluetooth, Wireless USB, ZigBee, ANT and proprietary solutions. The following chart examines the key selection criteria for a core technology:

	Physical Size (mm)	Node Cost	Reliability Security	Acceptance Adoption	Data Rate	Ease of Implementation	Power Consumption
802.11.x	12 x 12	$100	AES	High	54 Mbps	High	>500 mW
Wireless USB™	Unknown	$50-$75	AES	Low	480 Mbps	High	300 mW
Bluetooth™	7 x 7	$15 - $30	AES	High	723 kbps	High	50–100 mW
ZigBee	7 x 7	$7 - $10	AES	High	250 kbps	High	.5 to 50 mW
ANT™	5 x 5	N/A	AES	Low	1 Mbps	High	< 1 mW

Table 1

Physical Size

Physical component size may seem inconsequential when choosing a network topology. After all, processors and memory devices are getting smaller every day and in large machines panel real estate is not always at a premium. However, when considering applications such as Cytometry equipment that must fit on a table top and often has 12 to 30 axes of motion, the size of motion control electronics is no longer trivial. Processors, memory, antennas and radios all must take up the minimum of space to ensure that the size savings of eliminating cables is not consumed by overly large electronics. ZigBee offers one of the smallest physical footprints of any wireless network available today.

Node Cost

Of course, no machine builder wants to spend more than necessary on motion equipment. Therefore a network with a low cost per node is advantageous. ZigBee offers the lowest cost per node of any wireless topology on the market.

Reliability and Security

One of the most pressing concerns with any wireless network, motion or non-motion is reliability. A dropped node may not only be annoying, it may be dangerous to payload or machine operators and therefore must be avoided at all cost. A “self-healing” network is a desirable trait in a wireless network. As it turns out, ZigBee offers this “self-healing” characteristic in the form of mesh networking.

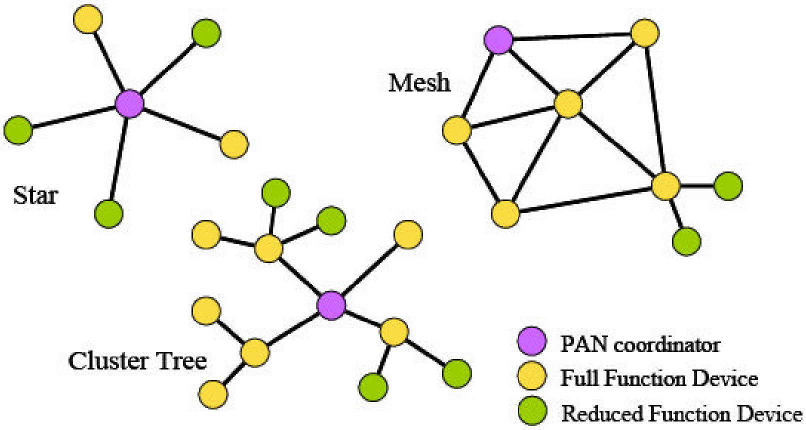

Figure 1

Figure 1 illustrates the flexibility of a ZigBee-enabled network. End nodes may be configured as Reduced Function Devices (RFD) for minimal power and footprint or as Full Function Devices (FFD) capable of routing messages. When end nodes are deployed as FFDs, end nodes may have a direct path to the coordinator or a multi-hop path via other FFDs as shown by the cluster tree and mesh implementation. In turn, if the existing path to the coordinator is compromised, ZigBee protocol can automatically re-route via another FFD as shown in the mesh implementation, thereby minimizing the risk of a dropped node. This functionality proves extremely useful in motion applications where obstacles (stages, etc.) may move and obstruct an end node's existing path to a coordinator. By re-routing, a new path is found and packet loss is minimized.

Another highly important consideration when choosing a wireless topology is security and data integrity. ZigBee is perfectly suited for such a task by employing Media Access Control (MAC) layer security for single-hop encryption and Network (NWK) layer security for multi-hop encryption as shown in Figure 2.

Another concern in wireless adoption is the ability to control networks. Ad hoc networks allow nodes to join and leave networks as necessary. Clearly, this is not acceptable in motion control applications where strict control must be maintained over a network structure. ZigBee protocol provides MAC and NWK level control over what nodes may join a network so two or more independent networks may operate in close proximity with no contention.

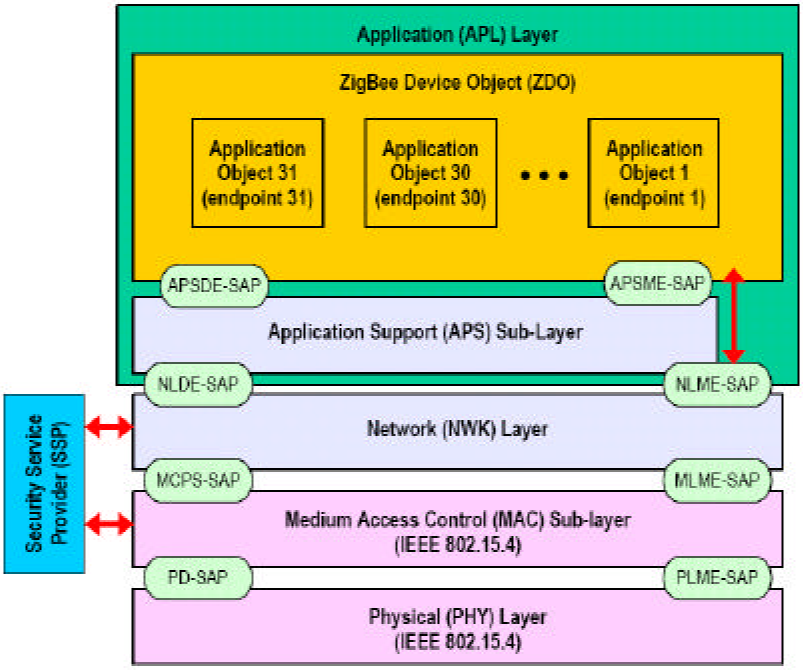

Figure 2

Data integrity is guaranteed via MAC layer calculations amounting to a CRC. In addition, an acknowledgement frame is sent by an end node upon successful receipt of a packet to further guarantee packet reliability and data integrity.

Acceptance and Adoption

With the exception of ANT and proprietary protocols most of the candidate wireless topologies have relatively good worldwide adoption. ZigBee is no different. As an open standard and commercially available wireless network, supported by multiple component and stack vendors, its inherently low-cost architecture and ease of implementation has gained rapid adoption in controls and sensor applications, particularly building automation. Worldwide, ZigBee supports the 868 MHz band in Europe, the 915 MHz band in North America, Australia, etc., and the 2.4 GHz band, which is now recognized to be a global band accepted in almost all countries. IEEE developed the physical layer and MAC layer standards. The ZigBee alliance, a multi-member, multi-technology group, defines the application and network layers while users develop application profiles.

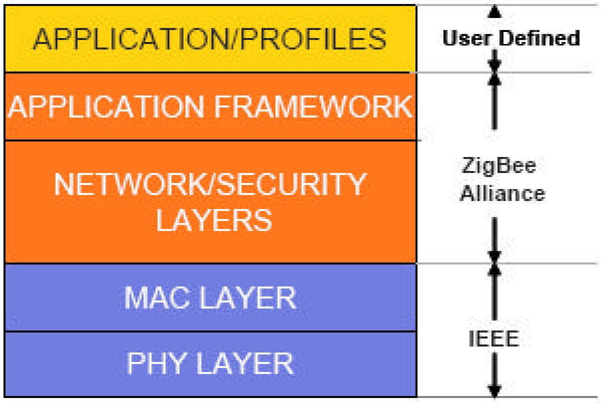

Figure 3

Many Prominent Fortune 500 companies embrace and back the ZigBee protocol and the ZigBee alliance is dedicated to expanding ZigBee technology and creating new profiles.

Data Rate

With much focus these days on network performance, one may wonder why ZigBee, a low data rate network, is considered the best choice for wireless motion control. The answer is found by recognizing the types of applications best suited for wireless motion control.

While Ethernet-based motion networks compete on performance to solve complex applications requiring tightly coupled motion and the highest bandwidth, they fail to address the needs of thousands of less rigorous applications. In such cases an Ethernet-based motion network may be overly costly and not address the most basic need to eliminate cable management issues altogether.

As an example, many life science fluidic applications have simple motion requirements for pump control and sample positioning. In such cases equipment as small as 2ft by 2 ft may have as many as 15 axes of motion. While the axis count is high and the axes may require basic coordination, the ability to tightly synchronize axes of motion to the microsecond is often not required. In these types of applications, the positioning or speed of the application is often more important than the ability to tightly couple axis positioning.

In many cases these “loosely coupled” applications are solved with CANopen or serial cabled networks with low data rates; therefore, it stands to reason that the lowest cost wireless network with a data rate similar to that of CANopen or other serial networks is the appropriate choice. In this case ZigBee is the perfect match. At 2.4 GHz, data rates as high as 250 kbps may be achieved.

Ease of Implementation

The ZigBee tagline is: “*ZigBee Technology: Wireless Control that Simply Works*” ? no wonder, as ZigBee offers ease-of-implementation advantages for motion control applications over other technologies. When evaluating a technology for use in motion control, one must consider the ease with which the technology may be included into a design. ZigBee is supported by several third-party software and hardware vendors with off-the-shelf radio, CPU and stack solutions, often in a single-chip. ZigBee’s protocol code stack is estimated to be about 1/4th of Bluetooth’s or 802.11’s. Antennas (i.e., SMA and chip-based) and antenna designs (i.e., PCB) are available for use in many varieties to suit the needs of individual applications. All of this allows for companies implementing ZigBee to offload the wireless design and focus on the development of their application.

Power Consumption

The initial desire of IEEE in the development of IEEE 802.15.4 was to create a low data rate solution with multi-month to multi-year battery life and very low complexity. Applications envisioned at the time were home automation, interactive toys and wireless sensors to name but a few, all of which operate on battery power. Due to the power electronics employed, however, motion control equipment usually operates via a single- or three-phase AC or DC power source. So the question is, how important is power consumption when choosing a wireless technology for motion control applications? The answer is very important and the following example illustrates why.

Consider a motion application with 20 axes of wireless motion:

- Case 1: 802.11 (Wi-Fi) Rx power is 667 mW (always on)@ 20 axes/machine & 1,000 machine installations = 13.3 kilowatts
- Case 2: 802.15.4 Rx power is 30 mW (always on)@ 20 axes/machine & 1,000 machine installations = 600 watts
- Case 3: 802.15.4 power cycled at .1% (typical duty cycle) = 0.6 watts.

Table 2

ZigBee devices will be more ecological than the alternatives saving megawatts at full deployment.

ZigBee Advantages

ZigBee offers advantages over other wireless technologies options. ZigBee offers a physical size and cost per node that makes it more attractive for cost-sensitive motion applications than Wi-Fi, Bluetooth or Wireless USB. ZigBee offers built-in security that neither Wi-Fi nor Bluetooth offer. The relatively low date rate of ZigBee contributes to its cost effectiveness and makes it a perfect replacement for low data rate fieldbusses and serial implementations. ZigBee gives developers the shortest and most straightforward path to implementation using low-cost devices and compared to other options ZigBee gives users the most energy efficient installation. Given the advantages that ZigBee offers we must now examine how to translate those advantages into a motion network.

Implementation

Centralized Motion Protocol

The advantage of a wireless motion system becomes more evident as the number of axes increases; however, the low data rate of ZigBee precludes a standard centralized approach, so a mixed approach is the best solution to ensure ease-of-use and also guarantee adequate performance and safety.

Wireless Motion Protocol is a mixed system comprising a centralized PAN motion coordinator and intelligent FFD motion nodes. The PAN coordinator fulfills the role of program and motion coordination while providing overall machine control functions from a single programming point to ease configuration. The FFD nodes are intelligent devices that implement de-centralized motion trajectory and local I/O information.

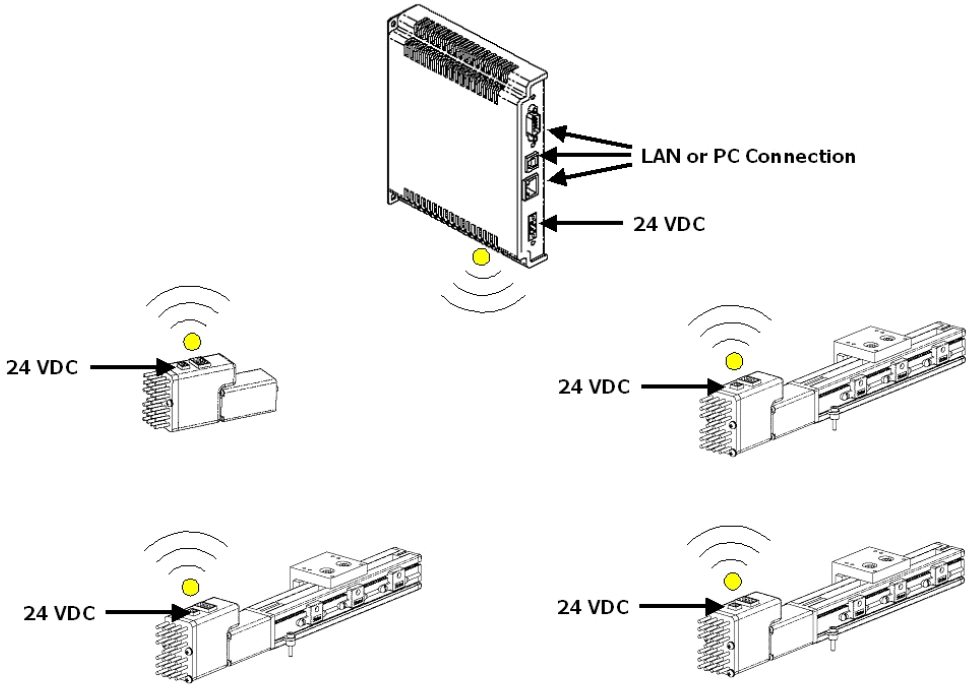

Figure 4

The FFD nodes are coupled to linear mechanical systems comprising an autonomous motion device. Up to 128 axes of motion are currently available although the theoretical limit is based on a 64-bit address. Up to 65,535 independent networks may be operated in close proximity to one another.

In general, the coordinator and end nodes incorporate the functionality as shown in Figure 5.

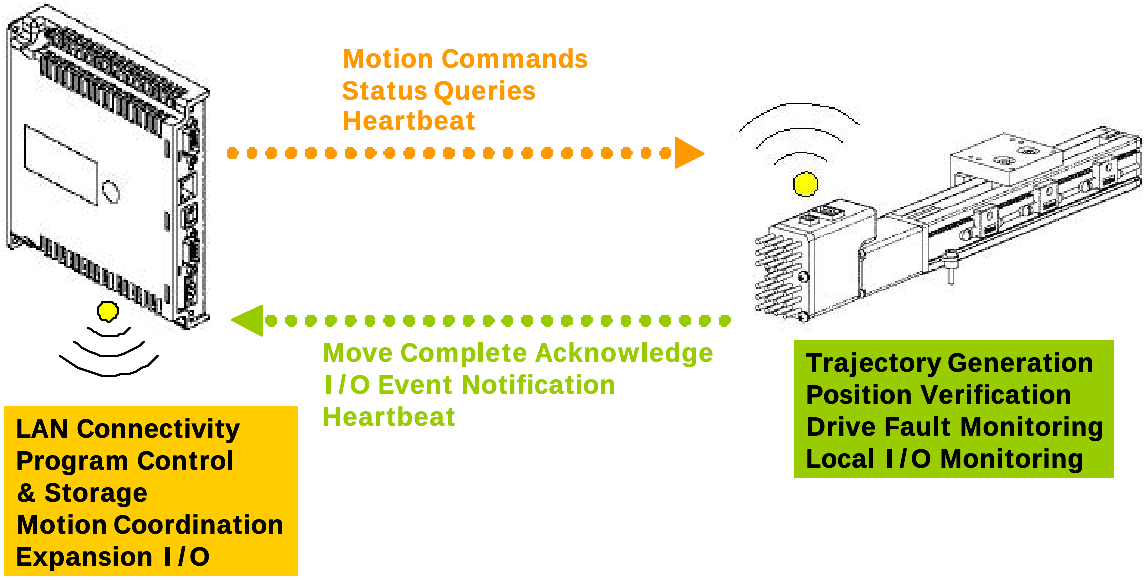

Figure 5

The mixed centralized and de-centralized implementation offers advantages by guaranteeing safety at the point of motion. If a drive fault occurs or an end-of-travel limit is encountered, motion is stopped immediately regardless of network state. In addition, local I/O wiring is minimized and terminated at the node. Finally, multiple axes of motion are accessible via a singe connection point. This patent pending approach will ensure that system costs are minimized while the safety and usability of the system are maximized.

System Configuration

Network configuration is simplistic and built-in to the MAC and NWK layers of the ZigBee stack. Each motion node is configured with a unique 64-bit MAC id and assigned a unique 16-bit short address once it joins the network. An integrated development environment provides the capacity to add or remove unique node addresses to the network.

Additional nodes may not join a network unless the user configures the network coordinator to allow it to join as shown in Figure 6. This allows multiple independent motion networks to operate within range of one another with no contention.

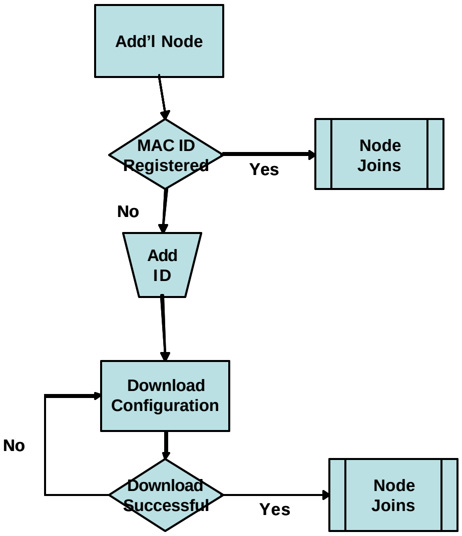

Figure 6

Frame Structure and Data Latency

As in any packet-based transmission, a defined frame structure is required to properly route and decode payload data to the correct end node. In the case of the wireless motion system, the data frame structure is pre-defined by the 802.15.4 MAC and is shown in Figure 7.

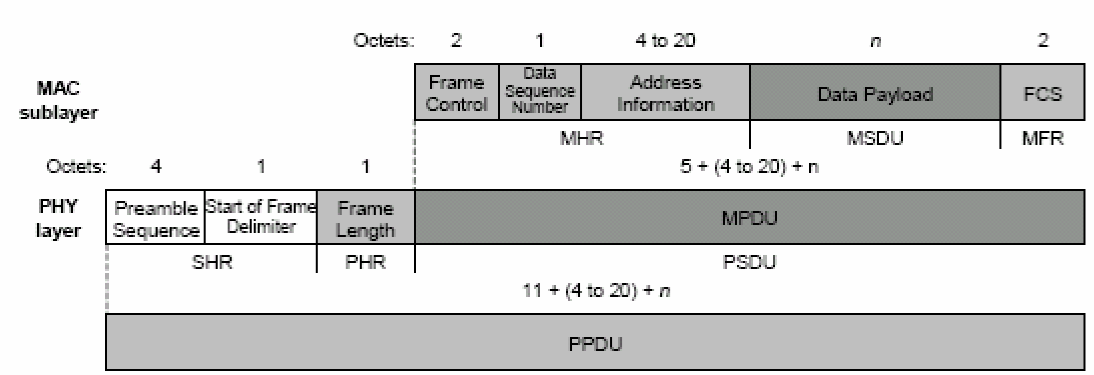

Figure 7

A typical data frame contains 15 octets of MAC and PHY layer frame overhead. In addition, the ZigBee application layer uses an optional 9 octets of overhead for profile and cluster IDs as well as sequence number to eliminate repeat packets. Finally, the data payload varies according to the operation performed but a typical value is 32 octets encompassing an acceleration, velocity, distance and move command. The total data frame size therefore is 58 bytes. Empirical testing shows that a 64-byte data packet sent via a one-hop Zigbee connection with an acknowledge frame executes in just 3 ms, including stack processing time.In comparison, a simple RS-232 serial bus with 8 data bits operating at 38.4 kbaud will transmit a similar packet of 32 characters at approximately 6.6 ms, assuming no CRC data check is employed.

Empirical Testing

The following testing summarizes empirical testing to date.

Throughput Testing

Test Setup:

1. Two coordinators (CN1, CN2)
2. Two test nodes (TN1, TN2)
3. Network A consists of CN1 and TN1 on channel 24
4. Network B consists of CN2 and TN2 on channel 24

Test Results:

1. Network A - no traffic. Network B issued single data frame (64 bytes of ZigBee packet). Average turn-around times between packet sent and acknowledge received is 3.2 ms. Worst case is 5.8 ms. There were zero packets lost.
2. Network A - maximum traffic. Network B issued single data frame (64 bytes of ZigBee packet). Average turn-around times between packet sent and acknowledge received is 8 ms. Worst case is 35.6 ms. An average of 1 re-try every 50 attempts (2%) was observed. There were zero packets lost.

This test illustrates that ZigBee is a robust network ensuring packet reception with interference and contention on the same channel. It is unlikely in practice that two networks will consume the same channel in close proximity and this test is considered worst case.

Duration Testing

Test Setup:

1. One coordinator (CN)
2. One test node (TN)

Test Results:

1. Repeated ping test
2. Two weeks of non-interrupted operation
3. 10,700,000 pings and ping response packets sent, only 2 repeat packets received and no packets lost

A repeat packet is likely caused by a missing or slow acknowledge; however, the packet content was not lost.

Obstruction Testing

Test Setup:

1. One coordinator (CN)
2. Two fixed nodes (FN1, FN2)
3. One moveable test node (TN)
4. One metal cage
5. Metal framing obstruction

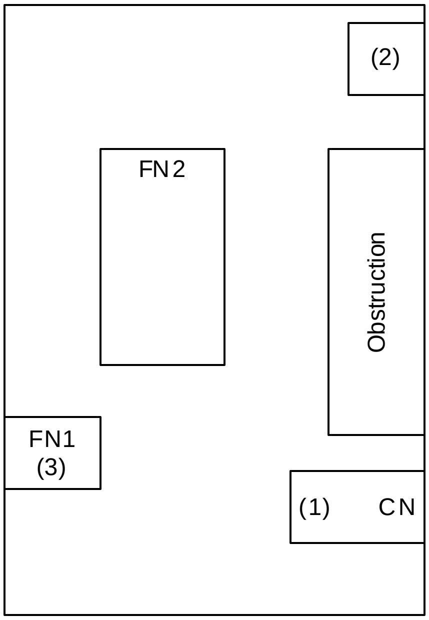

Figure 8

Test Results:

1. TN located at position 1 all packets received at all nodes (FN1, FN2, TN)
2. TN located at position 2 behind obstruction and inside metal enclosure resulting in re-route from CN to FN1 and TN. No dropped packets and all packets good after re-route.
3. TN located at position 3 and route from CN to FN1 and TN. Remove power from FN1 results in re-route from CN to TN, no dropped packets and all packets good after re-route.
4. TN located at position 2 inside metal cage resulting in re-route from CN to FN1 to TN. No dropped packets and all packets good after re-route.
5. Test node located at position 2 and powered down. All packets dropped and reported as errors.
6. Test located at position 1 and power re-applied. Orphan request by TN followed by re-route CN to TN and all packets received.

This test illustrates the effectiveness of mesh networking in packet re-routing. It was observed that the stack makes three initial attempts to send a packet to the end node. If no acknowledge is received, the routing table entry for that node is cleared. The application code then reissues the packet and the stack, seeing an empty routing table, will issue a route request to find a path to the missing node. A new path is established and the routing table updated before the data packet is successfully transmitted.

Range Testing

Test Setup:

1. One coordinator (CN)
2. One test node (TN)
3. Indoor building environment with metal walls
4. Daintree Link Quality Indicator diagnostic tool

Test Results:

1. TN moved linearly from 5 inches to 100 yards from CN
2. Link quality not correlated to linear distance. Link quality is higher at 100 yards than 20 feet
3. Ping test at all distances yielded no packets lost

This test illustrates that reflections off walls and other obstructions are a significant factor in the link quality. Reflections are more of a factor than distance. Mesh networking will significantly reduce the effects of reflections by guaranteeing path re-routing.

Although range is a wonderful marketing bullet, it is also a measure of how sensitive your system will be to outside noises. If your network resides in an area less than 25 square feet, you may not want to pick up transmissions from 100 yards away.

Orientation Testing

Test Setup:

1. One coordinator (CN)
2. One test node (TN)
3. CN and TN located inside EMI chamber
4. CN table mounted

5. TN mounted on moveable cart at distances of:
    - a. 1 ft.
    - b. 3 ft.
    - c. 9 ft.
6. CN antenna types used:
    - a. PCB
    - b. Chip antenna
    - c. External SMA antenna
7. TN antenna type used:
    - a. Chip antenna

Test Results:

1. CN and TN mounted in the following orientations:

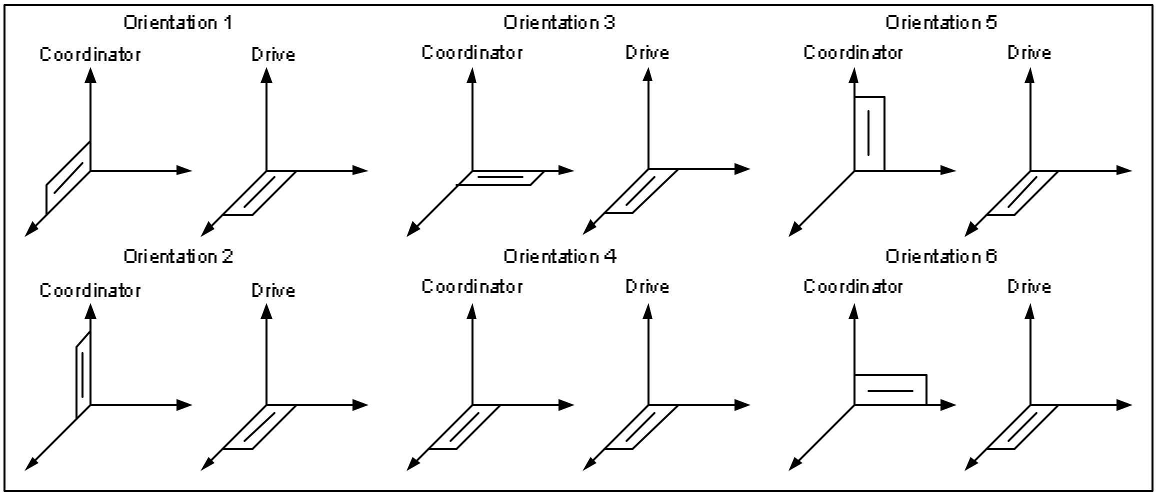

Figure 9

2. The Link Quality values with different combinations of orientation, distance and antenna types are shown in Table 3.

	Antenna																		
Distance (ft)	PCB1	PCB2	PCB3	PCB4	PCB5	PCB6	FRC1	FRC2	FRC3	FRC4	FRC5	FRC6	SMA1	SMA2	SMA3	SMA4	SMA5	SMA6	
1	180	168	168	184	120	144	156	123	180	168	100	148	180	120	132	176	132	128	LQI
3	160	152	132	136	108	124	116	134	124	100	72	96	152	116	120	160	131	120	
9	128	120	128	131	92	68	92	104	152	116	92	88	92	92	120	143	96	90	

Table 3

These tests are inconclusive. All three types of antenna perform well in the tests. PCB and SMA antennas appear to have the best overall performance while the chip antenna can be considered the lowest overall performance.

Summary

Wireless motion control offers a patent pending unique solution to the age old problem of cable management. Wireless motion control is optimally suited for high-axis count applications requiring “loose coordination.” Because of its mesh networking capability the system is extremely reliable resulting in zero lost packets. Although implementing a relatively low data rate network in ZigBee, the overall effective data rate approaches 115 kbps which rivals the low-cost cabled serial networks currently employed. Power consumption is kept a minimum level offering energy cost savings in-use. Finally, the ZigBee protocol requires minimal overhead and is straightforward to implement resulting in a low-complexity solution.