Developing Comprehensive and Extensible
Bluetooth Device-level Architectures
From the Ground Up

An Overview of Critical Design Challenges and Opportunities

Prepared by
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Overview

As the world moves inexorably into a wireless future, the Bluetooth standard represents a key linchpin technology, which can totally eliminate the hassles of cabling between conventional electronic components, while also opening up an exciting new world of integrated mobile devices, which are seamlessly inter-connectable and interoperable. Bluetooth-enabled products such as cell phones, PDAs, digital cameras, and notebook computers will revolutionize the ways that people interact with each other and their surroundings by breaking down proprietary barriers and providing automatic discoverability and transparent communication between disparate devices.

Although the opportunities are truly enormous, the realization of Bluetooth's projected wide-ranging impacts will only be achievable though the effective combination of several critical enabling technologies including reliable, low-cost radio frequency interfaces, efficient digital processing, and universally interoperable software to support both network and applications functions. According to Merrill Lynch's Bluetooth Handbook (Revision 1.1, June 2000), the market for Bluetooth chips will reach $4.3 billion and 2.1 billion units in annual shipments by 2005, however it also cautions *"the key barrier to entry is low-cost radio-frequency (RF) silicon technology."*

As will be described in this overview white paper, Silicon Wave has addressed this critical need for robust, low-cost RF silicon solutions targeted at helping developers quickly and efficiently create a full range of Bluetooth-enabled products. Key aspects of the Silicon Wave approach include leveraging a world-class team of technical experts and starting from the bottom up to define, design and implement a comprehensive low-power, high-performance, cost-effective and highly extensible architecture, which can support the predicted ultra high-volume ramp-up of Bluetooth market requirements.

The Bluetooth Revolution

Genesis, History and Industry Drivers

The Bluetooth technology was originated by Sweden's Ericsson and is named after Nordic king Harald Bluetooth, who is known for uniting Scandinavia in the tenth century. Similarly, Bluetooth today is providing the foundation for the wireless unification of diverse electronic devices in the twenty-first century.

In addition to Ericsson, the early proponents of Bluetooth technology included IBM, Intel, Nokia and Toshiba. In an unprecedented short time period, the Bluetooth wireless technology has become a worldwide de facto standard, providing the industry-accepted specification for small-form factor, low-cost, short-range radio links between mobile PCs, mobile phones and other portable devices. All of the Bluetooth standards and qualification procedures are controlled by the Bluetooth Special Interest Group (SIG), an industry group consisting of leaders in the telecommunications, computing, and networking industries that are driving development of the technology and bringing it to market. From its original five founding members, the Bluetooth SIG has grown to over 2000 members in the space of only three years.

Bluetooth devices communicate on an unlicensed radio frequency of 2.4 GHz, which allows them to be operated anywhere in the world without the constraints, costs and time delays of local country-by-country approval processes. Bluetooth uses a spread-spectrum with frequency hopping to provide robust connectivity, built-in security and multi-channel flexibility. The standard also includes auto-discoverable networking methods, which enable Bluetooth devices to be quickly and easily connected via ad hoc networks known as “piconets”.

Applications & Opportunities

According to industry analysts such as Cahner’s In-Stat Group, the year 2000 was primarily a development year in which Bluetooth technologies have coalesced and matured to set the stage for volume ramp-up of product shipments over the next few years. In addition to eliminating the need for cables between fixed computing devices, some of the first major opportunity areas will be with Bluetooth-enabled cell phones, PDAs and other mobile devices, whose users can gain immediate benefits from Bluetooth’s ad hoc networking of multiple devices on the go.

In effect, Bluetooth-enabled devices will be able to perform multiple functions, such as using your cell phone to access and carry out transactions to make purchases, fetch local directions or resources, check email, etc. Similarly, a Bluetooth-enabled PDA could automatically sync with other PDAs or laptops in a meeting to transparently share files being presented, collect business cards, manage shared calendars, etc. Or a Bluetooth enabled digital camera could be effortlessly connected to a photo-kiosk to up load images, produce immediate prints, store photos on the Internet and conduct the financial transaction to pay for the services; all in a single unified process.

Other Bluetooth opportunities involve using the technology to create personal area networks in which an individual user’s collection of Bluetooth-enabled devices all seamlessly communicate with each other, such as wireless headphones connected to a cell phone/PDA/MP3 player in a pocket and/or a laptop in the user’s briefcase. In addition, completely new and exciting entertainment applications are also possibilities, such as a demonstration project in Sweden in which spectators at a hockey game are able monitor players’ pulse, breathing, acceleration and player-mounted camera views, all via a Bluetooth-enabled wireless network within the hockey arena.

While the opportunities abound for an almost endless range of Bluetooth applications that promise to change the fundamental ways that we work, play and communicate, the realization of these possibilities will require robust solutions to the following critical technology challenges.

Critical Bluetooth Technology Challenges

Standards Compliance & Universal Interoperability

Obviously, a concept such as Bluetooth can only succeed if all of the Bluetooth enabled devices can be relied upon to provide universally consistent communications and interoperability. End consumers don't much care how or why the technology works; but they certainly care when it doesn't. The foundation for achieving such consistency and robustness lies in stringent adherence to Bluetooth standards, backed up by a rigorous testing and qualification process.

The current Bluetooth 1.1 Specification represents an extraordinary effort because from the beginning it was driven by a groundswell of international involvement from industry-leading companies, however at the same time it has developed independently of pre-existing standards-setting bodies. The Bluetooth SIG's strict qualification process guarantees that all Bluetooth products conform to the Bluetooth specification, ensuring interoperability among a variety of Bluetooth products and suppliers. This qualification is a necessary precondition of the free intellectual property license for Bluetooth wireless technology, and enables products to be labeled with the Bluetooth logo. In addition, the qualification of key component-level Bluetooth devices also can provide a reliable set of basic building blocks for product designers to quickly incorporate Bluetooth functionality.

Robust RF Performance in Inherently Noisy Environments

However, mere adherence to the minimal Bluetooth standards may not always provide a guarantee of acceptable performance in the longer run. Although Bluetooth leverages the availability of 2.4 GHz in the ISM (Industrial Scientific Medical) band to provide worldwide-unlicensed wireless connectivity, under real-world conditions, Bluetooth must cope with an inherently noisy environment. For example, the magnetrons used in standard commercial microwave ovens can become a major source of interference in the 2.4 GHz range.

In Bluetooth-enabled cell phones, the close physical proximity between the cell phone transceiver and the Bluetooth transceiver can represent especially difficult design challenges. In addition, as the sheer number of Bluetooth devices operating within a common area increases, the challenges become more difficult for quickly establishing inter-device connections as well as for maintaining required throughput and reliability levels, while minimizing co-channel interference.

As will be discussed in more detail in subsequent sections, the underlying RF design architectures used for Bluetooth must build in sufficient RF performance "headroom" to cope with dramatic increases in interference as the number of Bluetooth devices and piconets per device escalate dramatically in the foreseeable future.

Viable Cost Structures to Fuel Widespread Acceptance

Another key challenge in the development of commercially viable Bluetooth solutions will be the ability to achieve cost targets that enable Bluetooth wireless connections to be incorporated into a wide range of products and economically produced in ultra high volumes. Most industry observers agree that the cost of implementing Bluetooth connectivity will need to fall from today's $15-20 range to $5 or less in order to fuel unrestricted growth of consumer-oriented applications and widespread use of embedded Bluetooth capabilities.

However, managing the total-production-cost of different Bluetooth implementations is not a "one-size-fits-all" proposition that can be universally applied across all product designs. Each unique product development effort needs to attain an optimal balance of development costs, Bluetooth component costs, and total Bill of Materials (BOM) cost within an overall context of time-to-market issues, product ramp-up requirements and forward value-engineering opportunities. Achievement of both near-term and long-term cost objectives across a broad range of product requirements must begin with a fundamentally sound architecture, which allows for optimal partitioning of functionality, low-power operation, minimal support circuitry, fast time to market, efficient production ramp-up and on-going extensibility.

Software Integration Issues

In order to deliver on the goal of providing automatic auto-discoverable networking on an ad hoc user-transparent basis, Bluetooth products require seamlessly integrated software structures at a number of different levels. For the most part, Blue software requirements can be grouped into three major categories:

- Baseband Layer – from the RF wireless device to the Host Controller Interface (HCI)
- Host Protocol Layer – from the HCI to the Protocol Interface
- Applications Layer – from the Protocol Interface to the Application

Developers need to be able to efficiently implement all of the RF modem functionality and link-controller tasks in close integration with the hardware in order to ensure robustness and performance as well as minimizing requirements for developer to write laborious low-level code. In addition, developers need flexibility to implement the HCI and host-level applications software at the most appropriate levels within the architecture in order to achieve an optimal balance of performance, cost and product differentiation to maximize their competitive positions.

Here again, because of the critical interaction between the Bluetooth hardware and software, the fundamental low-level architectural choices made at the outset can end up making or breaking the overall effectiveness of the entire software implementation.

Assessing Architectural Issues and Tradeoffs

Many of the earliest Bluetooth designs evolved out of traditional wireless telephony approaches, such as DECT, and therefore tended to leverage existing legacy technologies, which have provided a quick path to demonstrable products but paid a price in terms of the inherent size and cost of the implementations. For instance, the use of DSP based schemes using existing digital signal processing components have required high chip counts and/or the use of sub-optimal multi-die packaging techniques, such as MCMs. As the majority of Bluetooth applications migrate toward embedded connectivity for ultra small mobile devices, the higher cost, power dissipation and large size of these first-generation approaches leaves them unable to meet emerging product requirements.

With a high degree of semiconductor-level integration having now become a key requirement for next-generation Bluetooth products, a number of issues still face the product designer with regard to the best architectural approach. On one end of the range, the use of full custom designs and/or Bluetooth-oriented Intellectual Property (IP) blocks represents an enormous undertaking in both resources and time-to-market that is impractical for most companies. On the other hand, the use of monolithic CMOS-based ASIC designs can lead to compromises in RF performance because of CMOS' inherent high frequency limitations. In addition, depending upon the particular product requirements, the use of monolithic ASIC designs for the entire Bluetooth interface can limit the designer's ability to partition the product architecture for optimal cost, size, power and functionality.

Another major architectural issue is the methodology used for converting between the RF analog domain and the digital processing domain, including whether or not to use intermediate frequency (IF) steps before reaching the baseband processing level. As will be seen, the tradeoffs between different approaches can have significant ramifications on the amount of circuitry, die size and power requirements of the Bluetooth devices.

As will be discussed in the following sections, all of these issues must first be approached from a comprehensive architectural perspective and then carried through a carefully considered implementation process in order to derive maximum near-term and long-term results from Bluetooth design efforts.

The Odyssey Bluetooth Architecture from Silicon Wave

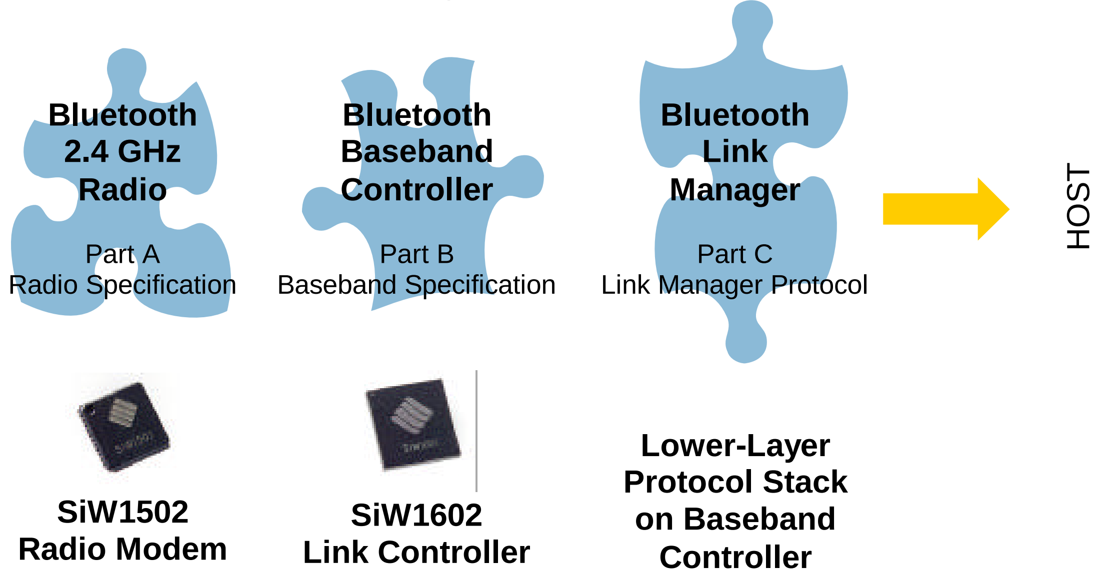
Silicon Wave, Inc. has been heavily engaged in developing Bluetooth interface technologies since 1998. As an associate member of the Bluetooth SIG and the Bluetooth Architecture Review Board (BARB), Silicon Wave is playing an instrumental role in helping to develop and refine Bluetooth technologies to create a firm foundation for implementing real-world Bluetooth application environments. By starting from a clean position of having no firm ties to particular legacy technologies, the Silicon Wave team has focused upon making fundamental architectural choices aimed at maximizing value to users and product developers, as well as building in technological extensibility from the very beginning.

Optimal Partitioning between RF, Link and Processing Functions

The Silicon Wave design team made an up front decision to partition the overall Bluetooth implementation into rationally defined segments in order to provide system-level designers with optimal integration flexibility and forward extensibility.

The first segment consists of a complete Radio Modem (RM) that implements the Bluetooth 2.4 GHz radio specification (Part A) while the second is a Link Controller (LC), which implements the Bluetooth Baseband Specification (Part B). In addition, the Bluetooth Link Manager functions (Part C) can be implemented in a lower-layer protocol stack on a standards-based digital Baseband Controller (BC) component such as an ARM processor.

Silicon Wave Architectural Segmentation



The SiW1502 Radio Modem IC combines low-cost, low-power consumption with integrated RF logic for a wide variety of Bluetooth applications. The chip is a fully integrated 2.4 GHz radio transceiver with a GFSK modem contained on a single chip. In October 2000, Silicon Wave's Odyssey SiW1502 Radio Modem IC received Bluetooth qualification, becoming the first single-chip radio modem in the world to achieve this distinction. In March 2001, Silicon Wave became the first company to pass Bluetooth version 1.1 specifications.

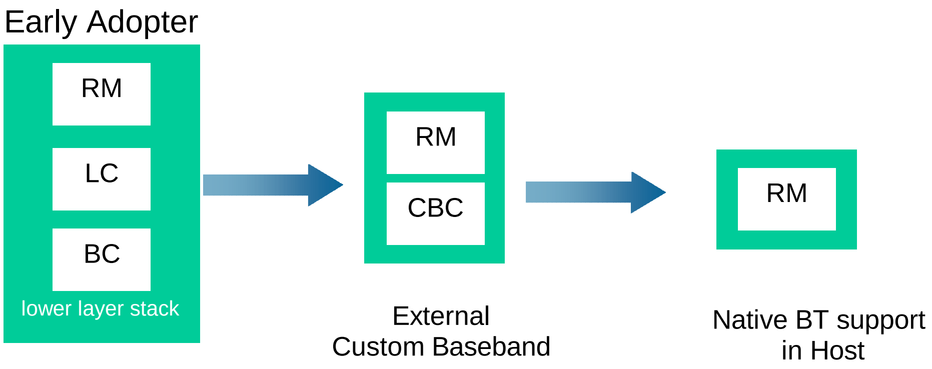
The SiW1502 chip can be used as a stand alone IC or, in tandem with the Odyssey SiW1602 Link Controller IC and a standard microprocessor, to create a complete

Bluetooth wireless communications system. The SiW1602 Link Controller IC interfaces directly with the SiW1502 Radio Modem IC and provides power control, data packet processing, error-detection/correction and other data processing functions.

In essence, the architectural segmentation delivers a complete Bluetooth-qualified solution for immediate use but still builds in the flexibility for each portion of the interface path to independently move forward to take advantage of new technology opportunities as they emerge. For example, because the RF portion of the Bluetooth interface is well defined and will change more slowly than other sections, the use of a complete RF Modem allows developers to immediately stabilize this critical portion of their product designs. On the other hand, many of the digital functions will require the flexibility to adapt to on-going changes as both application requirements evolve and digital semiconductor process technologies continue to improve.

In addition, the implementation of the entire Radio Modem function within a single device with a clean and well-defined digital interface to the Link Controller gives system designers much more flexibility for integrating the RF functions directly into their applications-specific designs. For example, many cell phone manufacturers looking to integrate Bluetooth functions are attracted by the possibilities of interfacing directly to the SiW1502 RF modem chip and integrating all link controller and upstream functions into their cell phone ASIC devices. As shown below, the rationally segmented Odyssey architecture gives them a smooth path of forward migration opportunities, ranging from a full 3-chip starting point through a custom 2-chip implementation or directly to a single chip Radio Modem-to-Host alternative.

Forward Migration Opportunities



By segmenting the architecture but clearly defining the interfaces between each segment, the Silicon Wave approach gives designers all of the building blocks needed for quickly developing cost-effective application-tailored Bluetooth designs today, while also allowing their applications to grow and evolve to remain competitive in the longer term.

Leveraging a Direct Conversion Receiver to Minimize Die Size and Power

Another key architectural consideration is determining the optimal methodology for converting from the analog domain to the digital domain. Conventional methods, such as DECT-based designs use superheteodyne designs that convert the RF signals to a relatively high intermediate frequency (IF) the demodulate the IF signal. This incurs a significant price and size penalty since filtering is required at the IF and must be performed off-chip. Similarly, designs that convert to Low IF or even Very Low IF frequencies still require significant amounts of intervening circuitry. This increases the overall die size and current consumption of the design. In addition because a large portion of the processing is necessarily handled in the analog domain, it is much more difficult to achieve required performance objectives for maximizing sensitivity and minimizing interference.

The use of a Direct Conversion Receiver that goes directly to baseband yields very significant benefits. Since the signal is translated directly from RF to baseband less analogue circuitry is required. This results in benefits such as smaller die size, less complexity, lower power consumption and overall improvement in the performance of the device. By doing a single conversion step directly to baseband and then going straight into a pair of A/D converters, Silicon Wave's Direct Conversion Receiver approach delivers maximum leverage from digital processing but without compromising on the performance of the RF front-end. Similarly, on the transmit side, the Silicon Wave approach uses a single conversion step directly to the output frequency to reduce complexity and minimize potential for generating unwanted interference.

Process-Independent Implementation Choices

Another key tenant of the Silicon Wave architectural approach is process-independence, which in effect allows the use of optimal implementation alternatives for today but does not preclude migrating various portions of the architecture to other semiconductor processes in the future.

Current Advantages of Using a BiCMOS Approach

For current product implementations, Silicon Wave has taken full advantage of advanced Silicon-on-Insulator (SOI) BiCMOS process technologies to deliver unmatched performance and reliability from the Odyssey architecture. The use of SOI BiCMOS yields direct and significant benefits in both boosting sensitivity of the radio receiver functions as well as minimizing interference generated by the transmit functions and complex digital circuitry.

Fundamentally, BiCMOS provides superior performance with regard to the bandwidth, gain (sensitivity), temperature independence, and noise characteristics when compared with mainstream CMOS or the more expensive RF CMOS processes. In addition, BiCMOS provides a significantly higher level of predictability, thereby making it more consistently reliable and robust in the face of inevitable process variations. Because bipolar transistors offer transconductance characteristics that predictably vary in direct proportion to the current, as opposed to MOS transistors whose transconductance is proportional to the square root of the current, bipolar devices take much less current to achieve a given level of sensitivity. In addition, bipolar transistors are extremely predictable across a much wider range of temperatures, thereby greatly reducing the need for complex temperature compensation mechanisms as required in many CMOS designs.

As shown below, Silicon Wave's current SOI BiCMOS implementation is able to deliver unmatched performance headroom for building robust Bluetooth product designs. For instance, while the Bluetooth 1.1 specification calls for a receiver sensitivity of –70dBm, the SiW1502 is able to provide a sensitivity of –83dBm, which represents a factor of 20 times better sensitivity than the specified requirements. From a systems perspective, this means that the designer could attain full Bluetooth mandated performance at a power level that is 20 times lower than would otherwise be required or could dramatically boost achievable distances at specified power levels. Obviously, in ultra-compact mobile devices, the ability to minimize power usage while achieving robust performance represents a key competitive advantage.

Odyssey
Radio Test Results

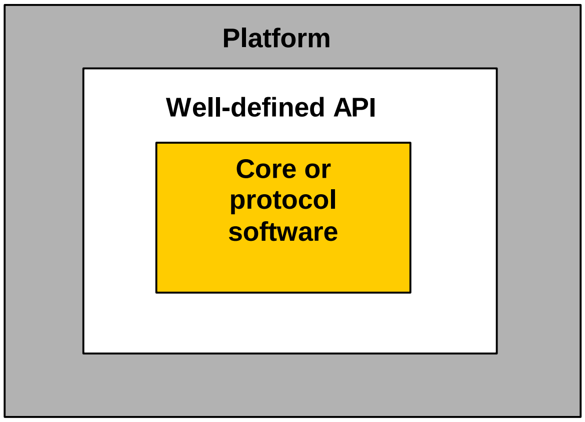
	Item	Bluetooth Specification	Measured
Transmit	Output Power	0dBm +4/-6 dB	3
	20 dB bandwidth	1 MHz	750 KHz
Receive	Sensitivity at < 0.1% BER	< -70 dBm	-83 dBm
	Adjacent Channel Rejection		
	Offset +/- 1 MHz	< 0 dB	-4 dB
	Offset +/- 2 MHz	< -30 dB	-40 dB
	Offset +/- 3 MHz	< -40 dB	-44 dB
	IIP3	> -16 dBm	-7 dBm

Potential Future Implementation Paths

While SOI BiCMOS provides the optimal implementation solution for today, the fundamental flexibility of the Silicon Wave architecture allows for a wide range of alternative implementation paths going forward. Because the Direct Conversion architecture moves directly into the digital domain, in the long run it provides the greatest leverage for tracking with future advances in mainstream semiconductor fabrication and packaging technologies. In addition, Silicon Wave's extensive investment in using advanced design and simulation tools for all of the Odyssey products has resulted in a solid foundation for quickly and efficiently migrating any portions of the architecture into the most appropriate future processes.

Comprehensive Software Support and Development Tools

As a complete “systems-oriented” supplier of Bluetooth solutions, Silicon Wave has also invested heavily in the provision of a robust software environment as a core aspect of the Odyssey architecture.



The full-range software offerings include:
- Core protocol software using 100% portable C code
- Platform software
  - Target specific C and assembly
  - Boot code
  - Device drivers
  - Operating system

By providing a well-defined API between the core and the platform level software, Silicon Wave has tailored the software environment to provide customizable complementary support for the modular hardware architecture. System designers are able to model and implement complete Bluetooth solutions using the full complement of Odyssey hardware components and then, if required, are able to migrate those solutions to target high-volume hardware implementations, while leveraging maximum reusability of their software investment.

Strategic Partnerships for Complementary Functionality

As a prime mover in the Bluetooth marketplace, Silicon Wave has already established in depth working relationships with many of the leading product developers who are currently building Bluetooth-enabled cell phones, PDAs, laptops and other mobile devices. The flexibility of the Odyssey architecture has proven to be very attractive to both customers and solutions-partners who are coming at the Bluetooth market from a wide range of different perspectives but who all require robust proven RF solutions.

In fact, the interface between Silicon Wave’s RF Modem and Link Controller is rapidly becoming a de facto industry standard, which many other Bluetooth device-level developers are already using to interface their solutions directly to the SiW1502 Radio Modem.

Silicon Wave, Inc

Corporate Background

Silicon Wave, Inc. develops and manufactures leading edge RF communications systems components for a range of different leading-edge applications. Headquartered in San Diego, CA, Silicon Wave also has direct offices in London and Tokyo, as well as a worldwide sales and support organization. With strong financial backing and a solid track record of developing semiconductor products for both the Bluetooth and broadband markets, Silicon Wave as already established itself has a leading supplier of advanced RF solutions.

Core Competencies & Strengths

From the beginning, Silicon Wave has been distinguished by an emphasis on bringing together a multi-dimensional engineering team, which can take advantage of proven expertise but is not hampered or constrained by being wed to specific legacy technology approaches. Silicon Wave is in effect a “systems company” that is able to channel extremely strong RF and digital design expertise into producing targeted silicon solutions for solving real-world communications challenges.

Many of Silicon Wave’s key technical staff members working on the Odyssey products have come out of in-depth involvement in the development of “smart cell phones” and other intelligent wireless devices. This has given them not only a valuable hands-on experience with developing low-cost, power-constrained RF devices; but has also provided them with a valuable understanding of the high-level objectives and a rich appreciation of the opportunities presented by Bluetooth technology. In parallel, the world-class expertise in advanced semiconductor processes provided by other team members has enabled the Odyssey program to leverage the best available implementation alternatives. Finally, the inclusion of highly experienced networking and software engineering resources has ensured that the Silicon Wave approach continues to yield complete Bluetooth solutions that are fully supported with development tools and that can be leveraged directly into creating successful real-world applications.

As a fabless manufacturer, Silicon Wave has established strong working relationships with leading semiconductor fabrication houses, including the most advanced BiCMOS, SOI, and leading edge sub-micron CMOS processes. In addition, Silicon Wave has the ability to bring other performance-optimized processes, such as SiGe, on an as-required basis. As described in previous sections, this enables the Silicon Wave design teams to consistently leverage the most appropriate implementation technologies rather than simply applying a pre-determined fabrication process whether it’s the best fit or not.

The Bottom Line

Silicon Wave’s comprehensive Bluetooth-qualified product set provides the industry with an officially tested and qualified solution that includes full baseband, radio transceiver and link management functionality. Original equipment manufacturers (OEMs) can design Silicon Wave's Odyssey solution into their consumer products and have complete confidence that they will pass the stringent qualification process. In some instances, OEMs that use the solution may not even be required to re-qualify the radio portion of their end products.

In a broader context, Silicon Wave’s highly-extensible modular Odyssey architecture has now laid the foundation for rapidly developing a wide range of best-in-class Bluetooth products that will help create and fuel high-volume consumer demand for Bluetooth functionality. In addition to providing the optimal solution for achieving near-term product introduction and time-to-volume-production targets, Silicon Wave’s Odyssey architecture also provides the optimal long-term migration path for on-going product differentiation, extensibility and sustained profitability.