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Design Process Changes Enabling Rapid Development

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ABSTRACT

This paper will address the electronic development in the wireless industry and compare it to the electronic development in the automotive industry. The wireless industry is characterized by rapid, dramatic high tech changes with a less than two-year cycle time and an equivalent life cycle. The automotive electronics industry is working toward reducing the typical 2 to 3 year development cycle down 1 to 2 years but with a life cycle of 10 years or more. In addition to realizing the electronic development benefits seen in the wireless industry, the automotive industry places significantly more emphasis on the quality and reliability aspects of their designs as many of them are targeted toward, or interface with, safety critical applications. One of the lessons learned from the wireless industry is the development process; where the hardware selection process can be accomplished in a virtual environment in conjunction with concurrent software development.

INTRODUCTION

Key aspects of automotive electronics and wireless industries share common successes made possible through the developments in semiconductor technology over the past 20 years. For several semiconductor companies, the wireless industry is leading the front-end of their technology development for commercial use. The increasing electronics capabilities introduced to consumers were realized through semiconductor technology that has allowed both industries to significantly impact the end user of their products.

As semiconductor technology development continues to evolve to the prediction of Moore's law, the trends of increased functionality, improved performance, reduced size and increased complexity can also be expected to evolve. This is true for both the wireless and automotive electronics industries. This trend provides opportunities to add more and more features and functions to existing products as well as up-integrate current products capabilities into newer products. The ability to sustain this technology growth rate is enabled by newer and more advanced system architectures. These new system architectures provide the performance and memory capability necessary to keep up with the performance and software growth required by the new applications, respectively. These technology trends will not only be realized through the increased complexity of the hardware, but also the increased complexity of product software.

All of this technology growth implies a higher product cost and increased engineering effort required to develop these new products. This trend conflicts with the business requirements of quicker time to market, minimizing product costs and increased profitability. In order to meet all of the technical and business objectives, corporations must manage project development cost by increasing the productivity and efficiency of engineering activities, reducing developmental spend rates, shortening product development times, and ensuring that the end objectives for product performance and delivery are met to schedule.

Today, everyone is benefiting from the latest convenience and productivity features made available by the wireless industry. Likewise, there have been substantial convenience and safety benefits afforded to the automobile consumer as a result of semiconductor technology development. While both industries have shared a significant number of commonalities, the wireless industry has been the true leader in the implementation of new technologies and methodologies used to achieve this success. The automotive electronics industry is using the same technologies and methodologies as the wireless industry, but at an introductory pace that lags wireless by about 2 to 3 years.

Making the economic problem more complex, corporate globalization over the past few years has moved at an unprecedented rate to capture and expand market share, better serve global customers and improve corporate efficiencies. This global movement has a significant amount of economic benefits to the corporate business metrics. But at the same time globalization opens a new realm of problems that will need to be solved. Problems like increased travel and information technology costs, communication barriers and additional capital and expenses associated with new or redundant engineering sites.

This paper will present an overview of the technology evolution associated with wireless and automotive industries, their relationship to the semiconductor industry and the key engineering and business objectives that drive success in the respective industry. The paper will then introduce the reader to the use of a software-simulation-based architectural model, often referred to as a "Virtual Prototype", as the primary development methodology for product design. The use of a virtual prototype brings a significant number of improvements in the development flow that will also be presented. This will set the stage for reviewing a case study of how a virtual prototype was used as part of a design methodology change in the wireless industry. The successful use of a virtual prototype for wireless applications will then be applied to a product development in the automotive electronics industry in order to predict the benefits this new design methodology might yield.

WIRELESS INDUSTRY

The wireless industry is large and intersects several markets: cell phones, wireless networks, consumer electronics (cameras, PDA, personal audio/video players, etc.) and automotive electronics (in-cabin communications, external safety, service & support communications). Over the past 20 years the wireless industry has made some incredible strides in reducing product size, increasing product features, and increasing the functionality and capabilities of their products, to list a few. Figure 1 details the history of wireless communication from its inception in the early 40's to the present.

In the late 70's and early 80's a cellular phone was contained in a hand bag the size of a large women's purse, had limited range, connectivity to an almost non-existent wireless network, sold for $1000 and was owned by a select few who's income was well beyond the dream of most average American families. In 2004, an average cellular phone is smaller than a deck of cards, can operate for days without charging, is capable of connecting to a well established wireless network in almost any part of the industrial world and is typically free with a service contract. Many families can now afford a cell phone for each member of the family. The wireless industry not only perfected the performance of the cellular phone over the past 20 years, but the size and weight decreased by 94% and 93%, respectively as compared to the first handheld phone produced by Motorola, Inc. which is shown in Figure 2 [1]. Today's cellular phones provide owners with additional capabilities of convenience, productivity and fun features such as built-in camera's, picture viewing, color displays, MP3 players, movie players, email, walkie-talkies, quick note messages, games, and in some cases, PDA functionality – something for almost every age group. An example today's cellular phone is also shown in Figure 2.

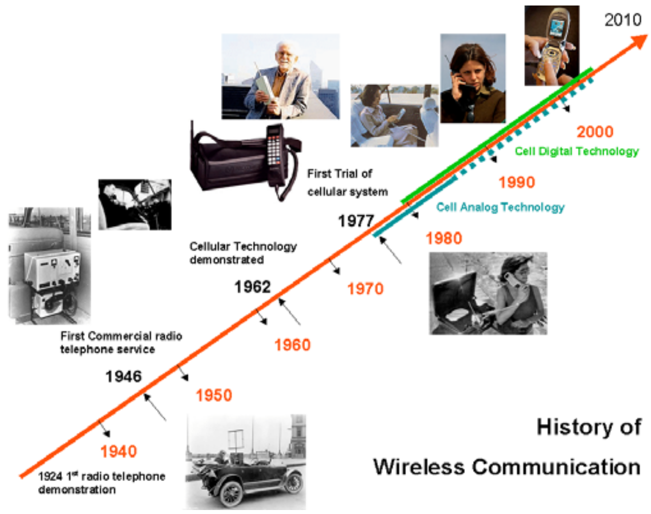

Figure 1 - History of Wireless Communications

	**The First Cell Phone (1973)** Name: Motorola Dyna-Tac Size: 9 x 5 x 1.75 inches Weight: 2.5 pounds Display: None Number of Circuit Boards:30 Talk Time: 35 Minutes Recharge Time: 10 hours Features: Talk, Listen, Dial
	**Typical Cell Phone, 2004** Size: 3.3 x 1.8 x .8 inches Weight: 2.8 ounces Display: 128 x 60 Pixel, 65k color Number of Circuit Boards: 1 Talk Time: Up to 5 hours Standby Time: Up to 8 days Features: Talk, Listen, Dial, Downloadable ring tones, Graphics and Games

Figure 2 - The first cellular phone developed in 1973 as compared to a 2004 cellar phone

Today, the wireless market can be characterized as follows: a high volume market (500 million units per year [2]), with a narrow market opportunity window of 2-4 months, moderate design cycle times of 12-24 months, and with software engineering dominating the design cycle rather than hardware.

The key focus of the wireless industry in order of importance is, cost, power and feature capability. Cost is a significant factor in almost every business, but it can be a more difficult problem in the wireless industry. This is because it conflicts with the need for newer/newest technologies, shorter product development cycles and the extremely competitive nature of the business. The products must also be designed to minimize the amount of power required to operate over long periods of time without recharging the internal batteries. Finally, with the higher performance requirements demanded by the introduction of new features and applications, the product must also have the throughput to be able to operate at a level where the end-user does not find the product to be cumbersome or awkward.

There is also a very important balance between design and program schedules that must be kept in order to ensure that the end product does not miss the required market introduction window. Failure to have a product available for the start of the intended market window may result in significantly reduced projected revenue if the introduction is late, to a complete loss of revenue if the window is missed entirely. This can have a significant affect on the company's revenues as seen in the decrease in market share when Motorola missed the window of opportunity during the switch from the analog to digital standard.

The clear trend is that market windows are narrowing and the total volume is increasing each year, although, the total volume is now composed of many model variations as specialization and personalization increases. Thus, common hardware platforms are developed in order to achieve product specialization and personalization through software, instead of hardware. As a result of this trend, software engineering is assuming an increasing proportion of the engineering process. At the same time, software complexity associated with these products is growing at an exponential rate as shown in Figure 3 [3].

To maintain a leadership position in this competitive and time-to-market driven industry, the development cycle at the semiconductor and wireless company is based on a significant amount of reusable technology as well as a continuous development cycle that allows for the introduction of new technology on a regular basis in order to improve the capabilities of the next generation products. The wireless phone developers using the ARM family of processors as part of the common hardware architecture is an example of this reusability.

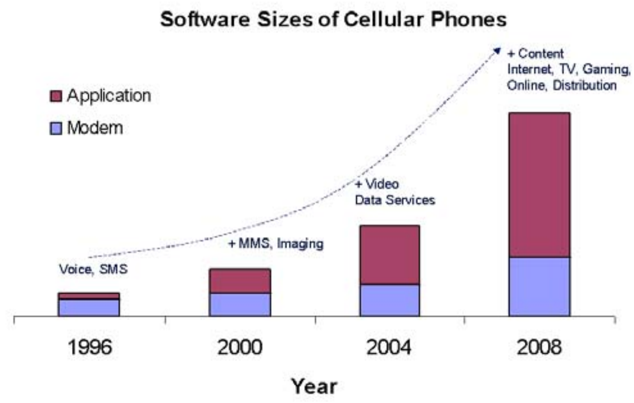

Figure 3 - Cellular Phone Software Complexity Growth Curve

The standard baseband architecture of a cell phone consists of a digital signal processor (DSP) plus a general purpose microprocessor (see Infineon's SGOLD2 architecture [4]). Modem functionality is executed on both processors, where after-office, multimedia applications are processed on the microprocessor (see Intel's PXA [5]). The trend for base-band architecture shows that the modem can be executed on a single DSP (see single core modem TTP [6]), and exploiting multimedia applications requires an additional microprocessor and optional hardware accelerators or/and a DSP chip (see Texas Instrument's OMAP architecture [7]).

The wireless industry is constantly designing new products and implementing advanced features, functions and styling in order to attract new consumers and maintain leadership in the market place. As shown in Figure 4, the hardware complexity has increased, but the total number of chips has declined as more capabilities are added even as chip size is reduced. This is the result of the rapid advancement of semiconductor technology used in the cellular phone.

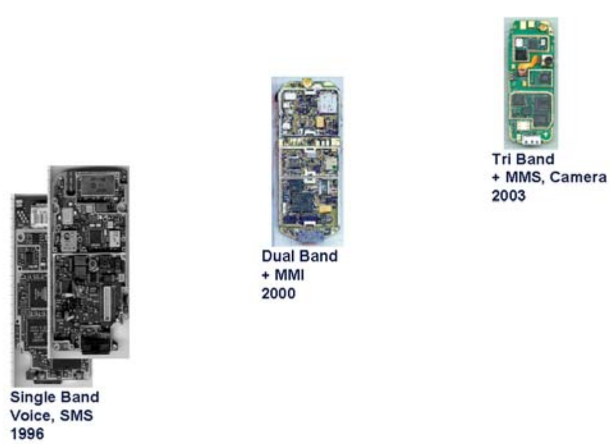

Figure 4 - Hardware Evolution for Cellular Phone

AUTOMOTIVE INDUSTRY

As with the wireless industry, the same 20 years has provided incredible strides for the automotive electronics industry, mainly resulting from the advancement in semiconductor technology. Figure 5 outlines the history of automotive electronics from the late 50's to present.

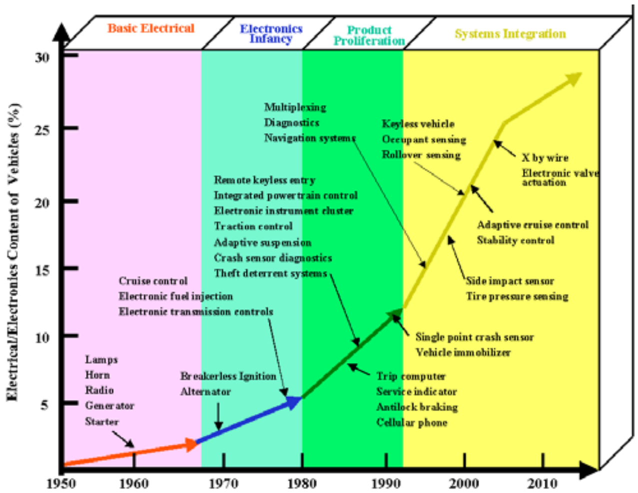

Figure 5 - History of Automotive Electronics, courtesy of TRW Automotive

In the late 70's and early 80's, electronics were making their way into the automobile for options such as theft deterrent systems, vehicle leveling control systems, instrumentation, air and body control functions in order to provide customer conveniences, and to provide closed loop carburetor control to help manage engine emissions. This was additional electronic content above and beyond the already well-established radio. The majority of these electronic features, with the exception of engine controls, were provided to the high-end automobile market.

Since the early 90s, **E**lectronic **C**ontrol **U**nits (ECU's) have been added to vehicles in order to improve the performance of mechanical systems. The reliability and performance of **A**ntilock **B**raking **S**ystem (ABS), traction and powertrain control systems has been greatly enhanced through the use of ECU's. Safety systems have made dramatic improvements in operation due to advanced control systems composed of electronics and software. In the near future x-by-wire systems will dramatically impact the design and performance of vehicles along with active safety systems. Telematics and personalization systems will also proliferate with many customization features similar to those offered in the wireless industry.

Today, the automotive electronics industry is large and can be characterized as having moderate volume with a total of over 50 million of cars and trucks per year [8] and an average of over 20 microprocessors in each vehicle. New model vehicles are introduced yearly, but require long design cycle times of between 24-36 months, development mainly dominated by software rather than hardware engineering.

The key engineering focus of the automotive industry in order of importance is quality/reliability, performance and cost. With respect to the quality and reliability objectives, the average life of a vehicle is 10 to 15 years with a warranty period of 5 years or 100,000 miles for the vehicle and the components depending on the make and model [9]. Developing a product that meets these requirements presents a significantly different design problem than that of the wireless product, where the environmental conditions are not as harsh and the average life is 18 months with a warranty period no longer than the average contract life of 1 year [10]. Ensuring that an automotive product meets the performance aspects associated with computing operation tasks in the specified time periods is no different that than a wireless product development. However, the automotive products are also required to meet an additional host of performance requirements resulting from the harsh automotive environment. Some of these requirements are extended temperature ranges, increased vibration and vehicle level voltage transients.

The quality and reliability expectations of the **O**riginal **E**quipment **M**anufacturers (OEM's)'s is rapidly becoming paramount as automotive electronics has encompassed safety related products such as Antilock Braking Systems, **P**assenger **O**ccupant **D**etection **S**ystems (PODS) and **S**ensing and **D**iagnostic **M**odules (SDM) for airbag deployment monitoring. It is imperative that these "safety critical" products work at all times and under all conditions. Failure to do so could result in serious ramifications to all those involved as well as warranty costs far exceeding the electronic product value.

While safety related products are a significant driver for quality and reliability improvements, OEM expectations are high for all automotive electronic product types. Beyond the safety issues and the OEM requirements, the customer expectations associated with buying a new vehicle drives quality and reliability standards for the entire automobile, including the electronic products it contains. The consumer is not willing to accept performance issues associated with a new vehicle that requires a return to the dealership to solve the problem. The vehicle is the customers' primary means of transportation. The inconvenience associated with this product failure is not tolerated well by any customer. While a cellular phone is typically given to the consumer at the signing of a contract, it is typically replaced free of charge upon return to the provider if it malfunctions and is often discarded at the end of the service contract. However, the automotive purchase requires a substantial out-of-pocket investment for the average consumer who finances, on average, $23,363 over 60 months with a resulting monthly payment of approximately $440 for a new vehicle.

While performance is a key common focus between the automotive and wireless industries, the performance aspect is carried further in automotive electronic products. Finally, as with the wireless industry, the automotive electronics industry is very heavily entrenched in minimizing the cost of their products. Many OEM's expect year-over-year cost reductions of as much as 30%. The year-over-year cost reduction expectations are driving design-to-cost initiatives and improvement in engineering efficiencies in order to shorten development time, meet the customer's requirements and maintain operating income.

As with the wireless industry, there is a very important balance in the automotive electronics industry between the design and validation process and program schedules that must be kept in order to ensure that the end product meets the required **M**odel **Y**ear (MY) introduction. In the automotive electronics business, the late introduction of any product for a MY launch is totally unacceptable. The risks associated with using leading edge technology for production development is one of the primary reasons why automotive electronics lags the wireless industry in technology use and introduction. A secondary reason is the quality and reliability expectations of the automotive electronic product to work without failure in an automotive environment for the life of the automobile.

In order to ensure that a design meets the functionality, quality and reliability requirements specified by the OEM, an automotive product will typically undergo at least one design verification and process validation cycle on the production intent system as well as four seasons of testing by the OEM prior to **S**tart **O**f **P**roduction (SOP) at the vehicle assembly site.

Throughout automotive history, the ECU's have shared a common hardware evolution that continues today and likely into the future. Semiconductor technology has been the primary enabler for the hardware evolution of electronic controls by an increase in features and functions, delivering higher performance, lower cost and higher reliability in a significantly smaller size. An example of this is shown in Figure 6.

As with the wireless industry, the clear trend is that design cycle times are narrowing, total volume of units sold remain flat, but model proliferation is increasing due to specialization and personalization. At the same time, semiconductor technology is enabling software to become a key technology for providing new features and functions to products as well as personal customizations to end users while maintaining a common hardware architecture. As a result, software engineering is starting to assume an increasing proportion of the engineering process.

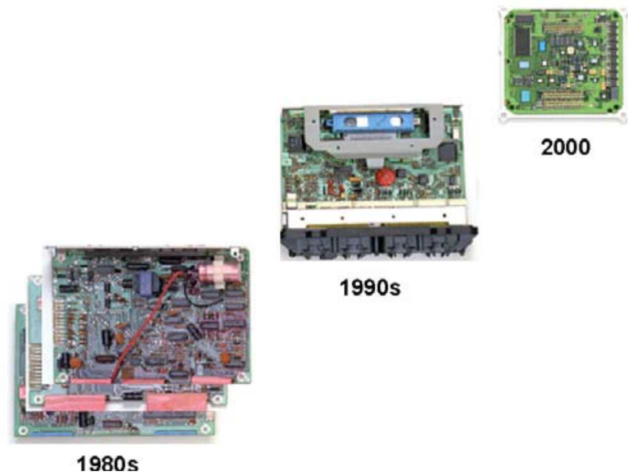

Figure 6 - Evolution of the Engine Control

Figure 7 shows the growth of software complexity for automotive product types over the past several years as a result of the enabling semiconductor technology and customer demand for product customizations and higher performance. [11].

Figure 7 - Automotive Software Complexity Growth Curve, Courtesy of Toyota

With the flexibility of software comes the increased engineering complexity of managing and developing the required features and customizations. Further complexity and development effort is required to integrate and verify the additional software on the actual hardware platform. These new complexities are placing an increased demand on software engineering resources, tools and methodologies in order to maintain or reduce program development schedules.

SEMICONDUCTOR INDUSTRY RELATIONSHIPS

The semiconductor industry has increased functionality, improved performance, reduced size and increased complexity of silicon solutions over time. These advancements have allowed the semiconductor industry to up-integrate many functions that were once typically implemented at the system level through the use of multiple **I**ntegrated **C**ircuits (IC's) or discrete design technology into a single IC solution. Today this up-integration has allowed the semiconductor industry to deliver an entire system and/or sub-system solution on a single piece of silicon. This industry has coined this capability as **S**ystem-**O**n-**C**hip (SOC). As part of an SOC solution, the semiconductor industry does not only supply the customer with an IC. In addition, they offer software drivers, algorithms as well as software development tools in order to increase the end-users productivity when using their silicon.

A key contributor to the advancements in semiconductor technology can be attributed to the design tool and methodology contributions of the **E**lectronic **D**esign **A**utomation Industry (EDA). The design tools and methodologies developed by the EDA industry have enabled the semiconductor design and manufacturing community to manage complex designs more effectively, automate complex or redundant engineering task, manage design process information throughout the development process, raise the level of design abstraction in order to simplify complex design problems, predict design performance earlier and more accurately in the development process and verify product performance prior to manufacturing. These improved capabilities achieved through the use of EDA tools have resulted in increased engineering productivity, increased product quality, reduced developmental expenses, improved portability of designs across manufacturing processes, reduce development time and the ability to design, verify and manufacture semiconductor technology on a global basis.

The fabrication development and design of semiconductor technology is driven in part by the wireless industry. While the cost to develop deep submicron process technologies and multi-processor integrated circuits is extremely high for semiconductor companies, the time from development to production is relatively fast. The total development cycle from concept to production is approximately one year for semiconductor process and design plus an additional year for system design and development at the wireless companies. This relatively short cycle time allows semiconductor and wireless companies to use leading edge technologies in the design of wireless products and start capturing some return on that initial investment with in the first few years.

This results in the rapid advancement of semiconductor technology used in the phone. Figure 8 shows the increasing gate count that has been realized over the past few years. The technologies first developed for the wireless industry are then expanded to other consumer, industrial and automotive technology markets. This allows the semiconductor companies to continue generating returns on their initial investment, keep fabrication facilities full and improve on the manufacturing learning curve that is required to meet the costs, yields, quality, reliability and delivery expectations demanded by the automotive market.

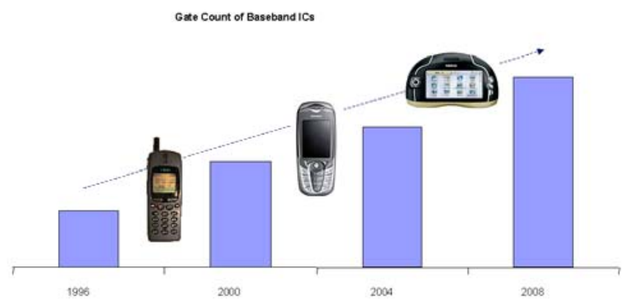

Figure 8 – Gate Count of Base-band IC's

Historically, the automotive electronics industry has required semiconductor companies to develop and supply mature and qualified devices. The primary drivers for using "more mature and qualified" technology in the automotive market are cost, quality and reliability. The cost of automotive electronics is managed to a great extent through the use of second-generation technology that was developed for the wireless and other leading edge industries. By using an older and more mature technology, the automotive market can minimize the high costs of new product development, reduce the risks associated with new technology development and introduction, and take advantage of manufacturing learning curves which all have a significant affect on the cost of the end product

INTRODUCTION TO VIRTUAL PROTOTYPING

The complexity of the physical hardware and associated software development required to achieve the new generation of products in both the wireless and automotive electronics markets continues to increase. In addition, an increase in "Time-to-Market" and "Design-to Cost" pressures continue to be demanded by corporate business managers, stockholders and consumers. In order to manage the complexity growth and meet the product development demands, it is extremely important to find more efficient ways to develop products.

One promising method that is likely to yield substantial returns for the engineering community is the use of virtual prototypes in the engineering development process. The virtual prototype consists of a computer simulation model of a large part of a system or an entire product that can be used by many, if not all, of the engineering design team members. They can develop hardware, software, test software, test equipment, and verification and validation vectors. As depicted in Figure 9, the virtual prototype methodology allows architecture, hardware, software and integration to start concurrently during product development in the absence of physical hardware [12]. This enables an earlier start for many engineering disciplines involved in the product design process and results in a shorter overall design cycle. Today, products are developed using a hardware-based methodology that tends to be more serial in nature. This serial development effort is typically a byproduct created by the absence of a physical prototype for other engineering team members' use as part of their development activities.

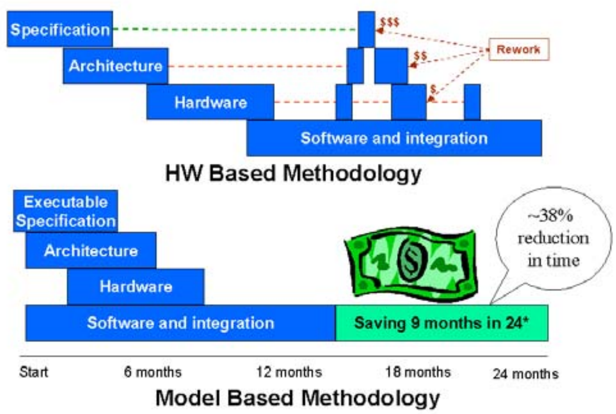

Figure 9 – Value Proposition, Reduction of Time and Money

The fundamental end result of introducing a concurrent engineering design approach is a reduction in total engineering time required to develop a product for production. This may seem like a huge benefit in itself, but there are often other benefits that are gained through the use of virtual prototypes. The virtual prototype can be used early in the development process to better understand hardware and software partitioning decisions and determine throughput considerations associated with implementations. Early use of functional models to determine microprocessor hardware configurations and architectures and the architecture of ASIC in development can aid in requirement capturing, functional performance improvements and expectations and documentation prior to or during the creation of the actual designs [13]. Working through application and system issues at this stage of silicon development can easily save a silicon revision prior to production. Depending on the technology, this can save $50,000 to $1,000,000 in mask charges alone [14].

Expectations are that the use of virtual prototypes along with well-defined and structured models can improve the quality of the target product through the use of excellent warnings and improved analysis tools that are made available by the use of a virtual prototype. This capability allows the engineering team more access to the product during development allowing problems to be found earlier in the development cycle and minimizes the rework affects on the physical hardware.

The same early use of the virtual prototype by the engineering development team can be utilized by the verification team to find problems early in the development cycle when influence on design changes are easier to accept and have little affect on the physical product or the manufacturing process. The system level verification process can realize additional benefits from a virtual prototype through the use of automated and/or self-checking test benches that can allow for un-attended twenty-four hours per day and seven days per week product verification.

The virtual prototype also promotes the efficiency of a global engineering workforce through its ability to be ported-to or accessed almost simultaneously by engineering resources located in corporate facilities worldwide. This allows for a virtual bench as well as a virtual prototype.

Finally, the virtual prototype provides a new level of product visibility that is not typically available to some members of the engineering team. Since the entire product is created in a simulation environment, access to internal probe points within the design is almost unlimited. This allows for detailed concurrent debugging of the hardware and software in the target system. The simulation environment also allows for scripting and regression testing which enhances the ability to introduce faults and understand system recovery, test and analyze communication path failures, and product ramifications associated with RAM and ROM corruption or PLL malfunctions. All of these items are very difficult to debug on the physical hardware. Overall, the use of a virtual prototype can result in the development of a better product, in a shorter development time, for less money.

CASE STUDY: WIRELESS APPLICATION

As depicted in hardware based methodology shown in Figure 9, the semiconductor supplier spends a year designing, fabricating and developing basic software for a microprocessor. When the device is ready, it is sent to the handset manufacturer who integrates the device and further develops the system software. Typically several turns in silicon are required during this process and it takes another year for the system to be fully integrated and tested. Figure 10 shows a detailed view of this process as it applies to the cellular phone development process.

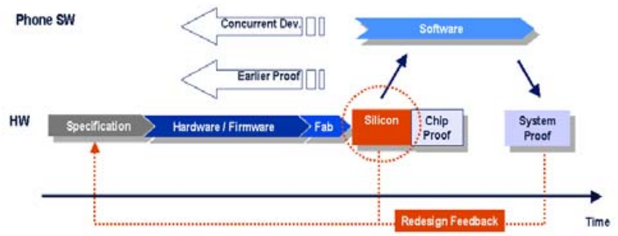

Figure 10 – Typical Cellular Phone Development Process

Figure 11 shows the detailed development process that result from using a virtual prototype methodology. With the use of virtual prototypes the semiconductor supplier can deliver a virtual prototype of the device to the system integrator 9 months earlier in the process. This means that the system integrator can start software development 9 months earlier and typically they can accomplish the final validation when the hardware is ready. At least one turn in silicon can be eliminated with this process.

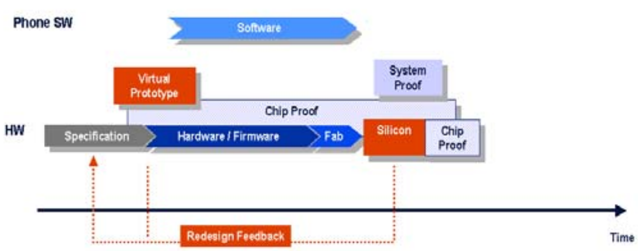

Figure 11 – Virtual Prototype Cellular Phone Development Process

For Infineon's latest 2.5G base band IC SGOLD2, virtual prototyping has been used to validate the chip specification and to provide an early system / software development platform. Using the VaST based virtual prototype of SGOLD2, new multimedia applications like video streaming were developed and validated prior to silicon. A graphical view of the SGOLD2 VaST virtual prototype virtual prototype environment as seen by the user is shown in Figure 12.

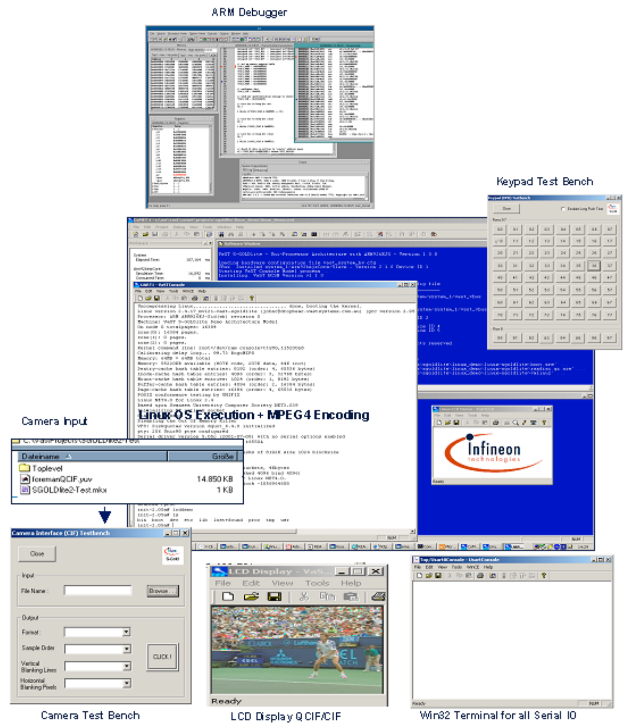

Figure 12 – Virtual Prototype of Wireless Base Band IC

CASE STUDY: AUTOMOTIVE APPLICATION

At this time, virtual prototyping technology is in its early stages of use and acceptance within some leading edge companies in the automotive electronics industry. This is not unexpected as the wireless industry is several months ahead of the automotive development efforts. This realization would follow the parallelisms between the two industries that are discussed throughout this paper. The use of a virtual prototype for development of an electronic product is one area where the gap in technology development and use between wireless and automotive electronics has been narrowed.

The application of virtual prototyping technology can be used at the onset of a new automotive product development as well as throughout the entire product development cycle. Multiple projects have been developed within Delphi Electronics and Safety to better understand the potential benefits and associated costs for creating and using a virtual prototype to develop electronic products. A virtual prototype case study of a complete ECU as well as a full custom **A**pplication **S**pecific **I**ntegrated **C**ircuit (ASIC) is presented in order to quantify some of the benefits of using virtual prototype realized to date.

VIRTUAL "ELECTRONIC CONTROL UNIT" PROTOTYPE - The virtual prototype of an airbag deployment module block diagram that is shown in Figure 13 was created within a simulation environment for use by a development team working on a production intent program. This airbag deployment module consists of a custom 32-bit microprocessor and 7 ASIC devices implemented as functional models that represent the actual behavior of the semiconductor technology used to create the physical hardware. The virtual prototype is capable of running the same compiled and linked target code as the physical hardware. In addition, the virtual prototype is cycle accurate in order to meet the real-time criteria associated with automotive electronic applications. The virtual prototype that was created for this project is capable of reading actual vehicle crash data into the simulation environment, can be used to verify system level serial communications performance, allows for fault injection and provides a scripting environment used to enhance product level testing. For example, several peripheral drivers have been found to re-initialize control registers without properly disabling the peripheral during the initialization process. All of these capabilities enhance the ability to verify compliance to the product to the customer's requirements. Since the virtual prototype is represented in a simulation environment, the capability of stimulating and monitoring functional nodes that are not typically available in the actual product also exists. This allows for better and more detailed checkout of the system than what could be achieved in the actual product. Finally, the virtual prototype provided the capability to gather performance data of the system in order to enable product level improvements.

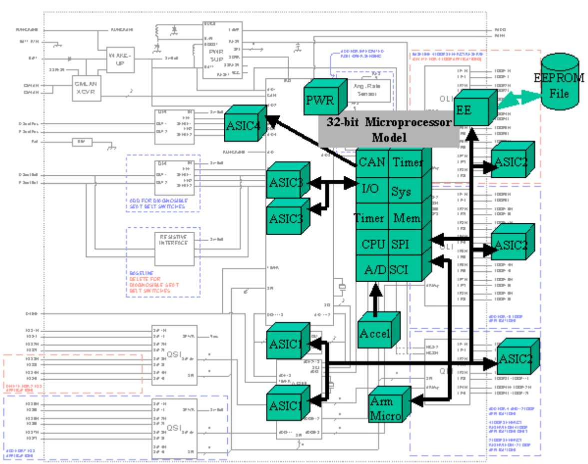

Figure 13 - Virtual Prototype Block Diagram

Figure 14 shows a graphical view of the user interface to the virtual airbag deployment prototype. The user interface allows for an in-depth view of hardware and software operation through the appropriate debugger interface as well as access to a graphical test bench that allows for control and monitoring of any desired system level signals and functionality.

In this case study, the virtual prototype for this project was not available to the development team until after physical product hardware delivery and was not used as the primary development path. This was a logistical problem associated with balancing program selection and calendar time. While the virtual prototype was not used as the primary development path for the end product, key design team members used it to quantify some of the benefits and refine the virtual prototyping process, environment and methodology. During the evaluation period the end-users cited the convenience, good visibility of the system internal nodes, accuracy and simulation speeds with high marks.

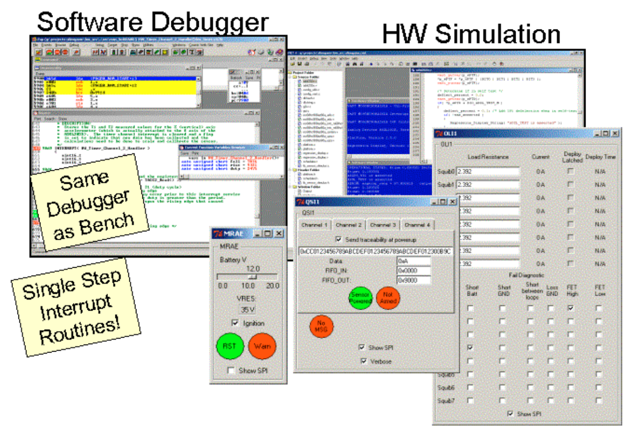

Figure 14 - Virtual Prototype Environment GUI

Like the virtual integrated circuit prototype project, there were a significant number of specification clarification issues that were resolved as part of the virtual prototype development process. Using the virtual prototype also allowed the development team members to highlight several specification issues where the design needed to perform differently than the original requirements. The visibility into the product hardware, software and the interaction between the two, provided by the simulation environment, allowed members of the development team to resolve several "difficult to find" software issues. As an example: A communications protocol is specified with a 3ms minimum inter-message gap for the receiver. The transmitter is designed to provide a 5ms gap. The 2ms delta between the transmitter and receiver specifications is provided as a guard band as part of the system architecture. The virtual prototype simulation checks for the 5ms gap and found a specific message sequence where the 2ms guard band was being violated.

Additionally, the virtual prototype was used to gather data for system level architectural studies and to estimate throughput requirements for future product functions and applications.

The benefits realized through this virtual prototype effort to date are summarized in Table 1. Because the virtual prototype was not the primary development path, most of the problems found were "early catches" found outside of the normal development process.

Benefits	Count
Specification Clarifications	> 100
Specification Errors	28
Software Issues	12

Table 1 - Virtual "Electronic Controller" Prototype Benefit Summary

VIRTUAL "INTEGRATED CIRCUIT" PROTOTYPE - Figure 15 shows a virtual prototype of a custom, mixed signal ASIC developed specifically for use in an airbag deployment module. Since this effort is targeted for production usage in a future model year application, the details of its functionality must be omitted to protect the intellectual property associated with this project. The development of this ASIC consisted of the integration of two existing mixed signal ASIC's as well as additional features and functions. In this case study, the development team created a virtual prototype of the ASIC directly from the system architecture and independently from the ASIC design team.

More than 30 specification clarifications were identified and resolved during the creation of the virtual prototype of the ASIC. These clarifications were probably not a significant threat to jeopardizing the required functionality or delivery schedule for the ASIC, but they would have caused potential communication and troubleshooting issues that would have certainly affected the productivity of the development teams in-house and at the ASIC supplier.

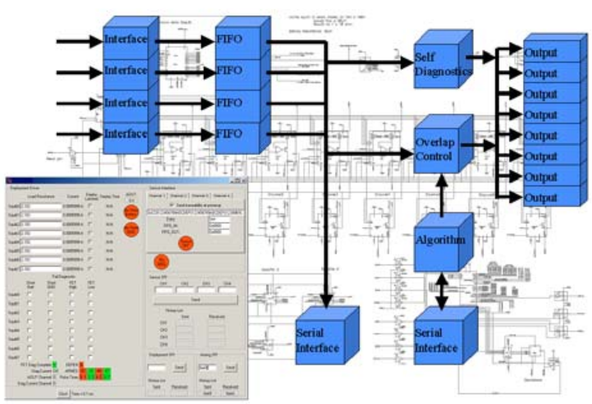

Figure 15 - Virtual Prototype Custom ASIC

There were 3 major functional issues identified during the virtual prototype of the ASIC as well. The first functional issue identified resulted in a complex functional feature being removed from the specification that in-turn saved silicon area and reduced the cost of the ASIC. The second and third functional issues resulted in a specification change to the device prior to the start of the ASIC design. At this stage of development it is difficult to speculate as to whether this problem would have been found prior to generating the fabrication tooling for the ASIC. For these problems alone, the creation of the ASIC virtual prototype saved anywhere from a few weeks of engineering design time to a full silicon turn by the supplier.

Finally, the ASIC virtual prototype was available for the systems and software engineers to start their development effort 6 months prior to receiving the 1st pass silicon from the supplier. Because the virtual prototype is being used for software and system development in a virtual prototype of the system application, the expectations are that the physical 1st silicon device can be up and running in the actual hardware system with less than a day of systems integration work on the laboratory bench.

This integrated circuit is still in development, but to date the benefits summarized in Table 2 below have been realized through the virtual prototyping effort.

Benefits	Count
Issues Resolved	>30
Functional Changes	3
Silicon Turns Eliminated	Potentially 1
Early Software Development Start	6 Months

Table 2 - Virtual "Integrated Circuit" Prototype Benefit Summary

At the writing of this paper, additional benefits are still expected on this project during the software development process. There is a planned exchange of system level test benches with the ASIC supplier for device level simulation and verification. The system level virtual prototype is able to simulate the integrated circuit at a "C-model" level and at the **R**egister **T**ransfer **L**evel (RTL). Both abstraction levels will include the analog portion as well.

CASE STUDY SUMMARY

Overall, all three test cases presented in this paper have realized substantial benefits to the use of virtual prototypes in the product development process. For the wireless test case, the use of a "Virtual Prototype" provided the following benefits for the semiconductor supplier and the cellular phone developer:

- Allowed for system level feedback in the semiconductor development process.

- Enabled a 1st pass silicon success for the semiconductor supplier and eliminated the need for a costly 2nd silicon revision.
- Provided a complete product software development environment to the cellular phone developers 9 months prior to silicon delivery.
- Resulted in a better quality product developed 5 months earlier than the standard design process was capable of supporting.

The benefits of using a virtual prototype for automotive electronic product development are not fully documented at this time. However, the initial data gathered to date from the automotive test cases discussed in this paper clearly show that the use of a virtual prototype will have the following significant impacts on improving the product development process:

- Improved product quality much earlier in the design and development cycle that results in an increase in engineering efficiency in the design process as well as better end-product quality.
- The capability to start developing application software earlier in the design process.
- The ability to supply a virtual prototype, in minutes, to all members of a development team regardless of their global location.
- Reduction in silicon turns for custom ASIC's.
- An improvement in the product documentation and requirements earlier in the design process where the impacts of any changes can minimize their affects on program timing and cost.

The engineering effort associated with developing a virtual prototype will put an increased burden on the product development effort early in the design cycle, but as shown in the wireless case study, it is expected that the rewards for the automotive electronics industry and the semiconductor suppliers will out weigh the associated costs of implementation.

The primary driver for reducing the long-term costs of virtual prototyping will be through the creation of a re-use library that will allow for rapid development of new architectures and derivatives of existing products. With this reusable approach, the long-term costs associated with moving to the use of virtual prototypes will quickly become insignificant.

CONCLUSIONS

The complexity of control systems in wireless and automotive products will continue to increase, even as the pressure to decrease the development cycle, decrease cost, and increase reliability mounts. The use of cycle accurate, high performance virtual system prototypes early in the systems engineering development process, prior to investment in the physical hardware, carries the promise of enabling engineers to cope with increasing system and controller complexity while addressing the imperatives of product quality and efficiencies in the engineering process.

In automotive systems, where ECU's are components of increasingly complex distributed control architectures, it is important that virtual system prototypes begin to model the whole automobile control system.

From the three case studies presented in this paper, the following predictions about the future of product development in the wireless and automotive electronics industries are being made:

- The pace of technology development associated with the wireless and other semiconductor technologies, along with the consumer pull for these types of products, will push newer technologies into the automotive electronics sooner than historically seen.
- The gap between leading edge technology used in wireless applications and the technology used in automotive electronics will continue to narrow over time at a slow rate.
- Product hardware and software will continue to grow in complexity in both the wireless and automotive industries. The interaction between the two will make the product and its associated development more complex.
- The newer and more complex ECU's will be used to form even more complex systems at the vehicle level. The development and interaction of these systems will become a significantly complex problem to solve. The architecture and verification of these systems will be challenging development efforts.
- New design tools and methodologies will play an important role in the development of these new and complex products and systems in both the wireless and automotive industries.
- In order to continue on the growth curve, the same evolution that took place in the semiconductor and EDA industry that increased the productivity and capability of the semiconductor design will need to take place at the system level.
- The automotive industry will have to adjust to new development approaches in order to meet the demands of greater system complexity (hardware and software) resulting from silicon technology advancements and shorter design cycles

Understanding and developing distributed control system is a major challenge for the future. Both automotive and wireless systems already employ such control. In this endeavor, there is no alternative to using cycle accurate, high performance virtual system prototyping as a central element of the engineering process.

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