X-BY-WIRELESS: A NOVEL APPROACH TO VEHICLE CONTROL

A Thesis

by

DAVID LOUIS HOELSCHER

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2006

Major Subject: Electrical Engineering

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ABSTRACT

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As the cost of wireless devices approaches zero, it becomes more feasible to replace wires with wireless communication. Vehicle wiring harnesses are traditionally wired to communicate both power and information simultaneously, resulting in separate circuits for each vehicle device. X-By-Wireless seeks to supplant this configuration in favor of a shared power bus and wireless inter-component communication. In doing so, we can recognize a number of benefits such as reduced weight and increased reliability, flexibility, and upgradeability. However, this introduces new problems such as longer transmission delays, interference and encryption issues, fusing difficulties, and public perception regarding safety.

The purpose of this thesis is to define the X-By-Wireless concept and to investigate the benefits and drawbacks in implementing X-By-Wireless. Furthermore, we do a theoretical and case study analysis to expand upon the weight reduction benefit so as to quantify the expected improvements. We also address each of the challenges presented by X-By-Wireless and integrate them into a proposed circuit that is capable of performing all the necessary functions of wireless control, wireless sensing, and fusing. We find that the proposed device can be mass-produced as an effective solution that meets the speed and security constraints necessary for most vehicle components.

To my wife Suzanne

ACKNOWLEDGMENTS

I would like to thank my professor, Dr. M. Ehsani, for his guidance and support in my research endeavors. I would also like to thank my committee members and the staff at Texas A&M for their dedication and assistance. Thanks also to my wife Suzanne who has helped sustain and encourage me throughout my research. Also, I would like to thank my dad for inspiring me to pursue engineering and my mom for instilling in me that there is more to life than academics. Finally, I want to thank the rest of my family and friends for the variety of ways in which they continue to support me.

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CHAPTER I

INTRODUCTION

In all vehicles, wiring harnesses are used to transmit power and control information between electronic components. These components may be used for sensing purposes, for control purposes, for driver display, or variety of other tasks. As the number of electrical components in a vehicle increase, the wiring harness which connects these devices becomes larger and more complex. To alleviate this complexity, some vehicles have begun to employ a Controller-Area Network (CAN), which uses a common data bus for all vehicle components.

This research takes the concept of a common vehicle data bus a step further by completely removing the wires used to transmit information. The concept, referred to as X-By-Wireless, is based on the principle that information transmission is not restricted to any particular medium. In the last century, information transmission has progressed from the mechanical domain of writing on paper to the electrical domain of controlling voltage. As the cost of wireless devices approaches zero, it becomes possible to make another such transition into the wireless domain. Using wireless technology effectively can provide variety of benefits, many which are not yet known, much like advent of computers would have been difficult to predict a century ago.

This dissertation follows the style and format of *IEEE Transactions on Industry Applications*.

A. Modern Vehicle Electrical Systems

Vehicle wiring harnesses transmit both power and information to their attached components. Often each vehicle component or system is provided with a dedicated electrical circuit. This configuration results in separate power networks which typically operate at a common voltage. This setup is evident in a wide variety of vehicles including cars, boats, and airplanes. The typical automotive wiring harness weighs at least 5 kg. In addition to this weight, there is additional mass in the form of a fuse box, which contains fuses that provide short-circuit protection for each vehicle system.

Some newer vehicles use a CAN system to facilitate inter-component communications. CAN uses a priority-based communication technique, in which a high-priority component is guaranteed to transmit messages before lower-priority components [1]. Although CAN systems are able to reduce some of the vehicle wiring, the need for separately fused circuits indicates that we can still reduce the amount of wiring.

B. Future Vehicle Electrical Systems

Modern vehicle trends point towards a More-Electric Vehicle (MEV) in the future [2]. Drive-By-Wire, increased vehicle electrification, and automotive hybrid-electric drivetrains are evidence of these trends. Indeed, the electrification of the vehicle has increased the power load to the point where higher system voltages are being used. There are indicators supporting a transition to 42 V [3], and hybrid-electric vehicles such as the Toyota Prius already use storage batteries operating at several hundred volts [4].

To control these loads, more sophisticated control mechanisms will be used. Fig. 1 shows a potential layout for the future vehicle electrical system. One the right side of the figure, there is a low-voltage DC bus which uses remote modules to control individual loads. The remote modules themselves are controlled by the Power Management System. This control information can be communicated through a variety of medium, including electrical wires, fiber optics, and wireless devices. We will focus on the use of wireless technologies as a communications channel.

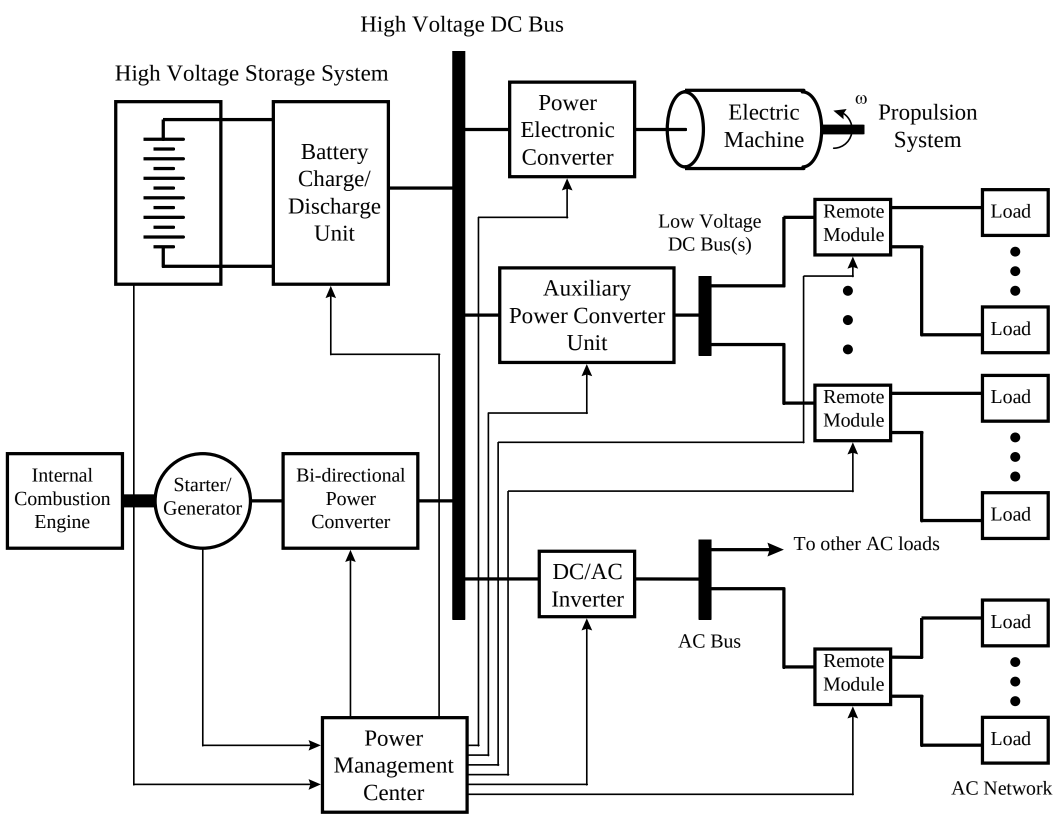

Fig. 1. Advanced vehicular electrical distribution system architecture [5].

1. Power and Information Decoupling

The most significant factor in future electrical system architectures is the decoupling of power and information. Modern architectures inherently tie these two roles together; if there is a voltage present on a wire, the electric current through that wire is used to power the connected device. To turn off the device, the electric current is stopped and voltage is removed from the wire. This implementation is suitable for a system that consists of very few devices. In this case, the additional overhead of a separate control communications system is unnecessary, and indeed it was unnecessary in early vehicles. At the present time, however, this implementation is beginning to outgrow its effectiveness. By separating power and information transmission into two separate systems, we can realize much simpler, more flexible, and physically smaller implementations.

2. Increasing Component Count Trend

Vehicles of all types have more electronic components than ever before. In the automotive sector, there have been developments ranging from power windows and power door locks to GPS navigation systems and DVD players. On airplanes, in-flight phones and in-flight movies requiring headphones are now commonly available. Fig. 2 shows an average count of circuits and connector pins in vehicles over a progression of time. The slope of the line appears to be strictly monotonic and shows no sign of slowing down. The Drive-By-Wire concept itself indicates that even more vehicle functions will become electrified in the future.

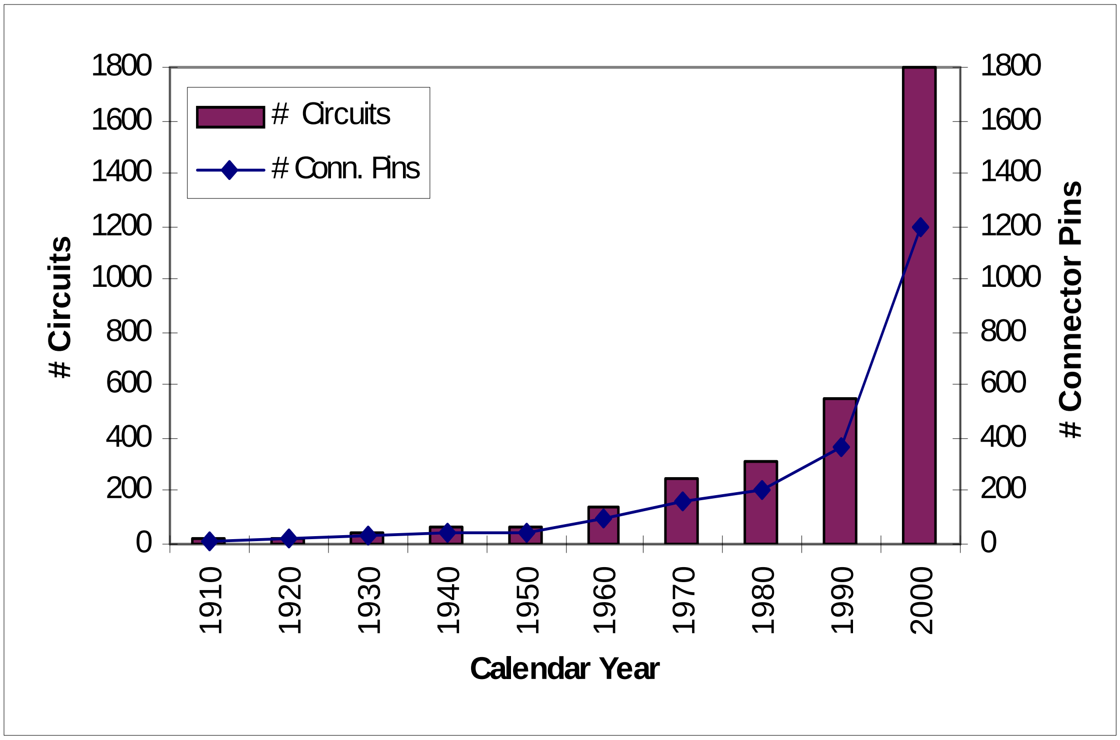

Fig. 2. Average number of circuits and connector pins in automobiles vs. time period [5].

C. Drive-By-Wireless

The Drive-By-Wire concept is popular in the automotive sector. It purports the replacement of traditionally mechanical systems with suitable electrical counterparts. For example, the traditional steering column in a vehicle uses mechanical linkages to communicate the driver steering commands to the wheels. This system incorporates a fluid pump to assist with the steering effort, a centrally located rack and pinion, and joints to give the steering column vertical flexibility. In contrast, a Drive-By-Wire implementation would electrically sense the position of the steering wheel, communicate the position information to an electric motor at the wheels, and the motor would control the direction of the wheels. This reduces many of the physical constraints surrounding the steering column. For example, it would be much simpler to toggle between vehicle manufacturing processes for the United States and England because the steering wheel could be placed on either side of the vehicle with only superficial mechanical differences, such as the dashboard configuration.

The Drive-By-Wireless approach goes one step further and eliminates even the electrical wiring constraints. For example, when performing vehicle diagnostics automotive maintenance personnel can use a wireless system to pinpoint problems before they even open the hood. There are already some signs of wireless systems being implemented in a small scale, such as remote door locks. However, no vehicle manufacturers have made the leap to a fully wireless system, in which the primary communication method for every component is wireless. An automobile which does employ this technique would be characterized as a Drive-By-Wireless vehicle.

Until now, most wireless systems present on cars exist because their only practical implementation required it. Radios, remote door locks, and remote vehicle assistance (such as OnStar) only make sense in the context of wireless devices. There are some components that can be implemented with a hardwired solution, but the wireless benefits were obvious enough that a small-scale wireless solution has proven more feasible. For example, tire pressure monitoring systems are much simpler to implement wirelessly because they exist within the wheel itself and are thus on a rotating frame of reference with respect to the rest of the vehicle. Prior to the wireless tire pressure monitors, slip rings were used to maintain electrical contact.

D. X-By-Wireless

There is no reason that the benefits of an inherently wireless system should extend only to automotive applications. When applied to any vehicular technology, the Drive-By-Wireless concept is more generally referred to as the X-By-Wireless concept. Different vehicle types will find certain benefits greater than others. In a train, if a wireless approach is used to control braking, then we find that we can reduce the transport lag found in hydraulic braking, which can become significant when stretched across the length of a train. Alternatively, if we use a wireless system in an airplane, we can observe some weight reduction which impacts fuel consumption. Also, the longevity of aircraft results in regular equipment upgrades and retrofits of new systems. An X-By-Wireless aircraft is much easier to upgrade than a traditionally wired aircraft because there are fewer constraints with regards to routing new wiring.

E. Problem Statement

This thesis revolves around the central question, “Can we make vehicles that use only wireless technology for inter-component communication, and is it worthwhile to do so?” To answer this question, we characterized the vehicle, considered the ramifications of such a system, determined if it is feasible, and identified both supporting technology and gaps in technology.

F. Conclusion

The X-By-Wireless concept provides a number of benefits to transportation technologies. Traditional wiring techniques are becoming increasingly complicated and heavy due to high component counts, they are difficult to upgrade, and they have a fundamentally static layout. Comparatively, X-By-Wireless systems can cost less, weigh less, have reduced copper losses, have a longer range, and be simpler and more upgradeable. Additionally, the increased flexibility of wireless systems indicates that there is room for novel components that take advantage of the benefits realized in an X-By-Wireless architecture.

CHAPTER II

MOTIVATING FACTORS FOR X-BY-WIRELESS

Before making major changes to any system, it is necessary to first justify the changes. If the justification is shown to produce a net positive result, then it is reasonable to make the proposed changes. In the case of vehicle wiring harnesses, it is tempting to suggest that existing wiring harnesses are adequate solutions, and that there is no need to consider alternatives. However, to follow this line of thought does not consider present trends and future bottlenecks.

Wiring harnesses have been getting bigger and more complicated, and at some point, if the trend continues, the wiring harness will be an impractical solution for vehicle communications. Additionally, wireless devices are approaching zero cost. These and other observations combine to form a situation that fosters the use of wireless technology as a prime-mover of information in vehicles.

First, we will look at problems with existing wiring harnesses. Some of these problems are so subtle and considered acceptable that they are not considered problems until compared to the improvements gained by a wireless system. Then we will look more closely at the benefits of X-By-Wireless implementations.

A. Drawbacks of Modern Vehicle Harnesses

When the steam engine was invented, the centrifugal (fly-ball) governor was used as an automated control system. It was mechanical in nature, yet it provided the necessary control for reliable engine operation. One of its biggest drawbacks was that it was fixed to operate the engine near a particular operating speed. This was acceptable at the time, but as engines became more sophisticated and used for a wider variety of applications, it became necessary to use a more flexible control scheme that allowed operation at various speeds [6].

Likewise, the wiring harnesses in modern vehicles are restricted in ways we do not readily perceive because thus far, they have met the minimum necessary requirements. However, in addition to their fundamentally static layout, they are becoming increasingly complicated, they use a wide variety of connectors, they add unnecessary wire weight, and they make the vehicle difficult to upgrade.

1. Increasingly Complicated

Numerous vehicle components must communicate among themselves in modern vehicles. For example, most automobiles with an automatic convertible top will not allow the top to come down if the transmission is not in park. Furthermore, some automobile features are disabled if the key is turned off, some are enabled when the key is turned to “accessory” mode, and all components can be powered when the vehicle is on. Thus, in the case of simply putting down a powered convertible top, we must have wires that connect to a controlling switch, the shift sensor, the key assembly, a controlling device, a fuse, and the battery.

Taking into account both the existing system complexity and the trend toward increasing component count, it is expected that we will continue to see increasingly complicated wiring harnesses to ensure adequate inter-component communication. The

X-By-Wireless approach would seek to minimize these complications by allowing any device to communicate freely with another device. Effectively, all components could communicate on the same channel wirelessly. In doing so, the physical connection between components will consist of only a single power bus.

The CAN protocol also attempts to reduce wiring harness complexity. However, the X-By-Wireless concept can extend it even further. Because the CAN protocol is still wire-based, the notion of a fuse box is still present, which results in individual circuits for individual components. Although certain X-By-Wireless techniques can be employed in a CAN-based system to reduce the circuit count, the CAN protocol in itself does not substantially reduce the circuit count.

2. Connector Variety

Systems that separate power and information transmission benefit from a reduced connector variety. For example, within a typical desktop computer case, the power bus and information bus is clearly separated into two distinct wiring harnesses. As a result, we find that there exist only three or four different types of power connectors. Most hard drives and CD/DVD drives use the same higher current-rated connector, and most cooling fans use an appropriately lower current-rated connector. When compared to the connectors available in a vehicle such as an automobile, there is a striking difference in the design approach. Almost every vehicle component type uses a separately designed connector. The rationale behind this technique is that it prevents assembly errors—if a certain plug fits into only one component, then it must be the right plug for that component. Unfortunately, this also results in a large variety of connectors on a single vehicle. Indeed, we find almost a new connector for every type of device. Fig. 3 shows a subset of the connector varieties found on a typical vehicle, a 1995 Dodge Neon.

In a corresponding X-By-Wireless system, we would find very little connector variety. Because the devices operate on a common power bus, the only variety we can expect would be for different power consumption. A high-power device, such as vehicle ignition, would need larger wiring and thus larger connectors. Aside from that, the connectors would all be interchangeable. In addition to making assembly faster and easier, it reduces the initial connector costs and allows for easier upgrades and more universal upgrade kits. Finally, because the connector is used only for power delivery, many connectors become smaller. The figures in the lower right of Fig. 3 attach tens of wires to their respective devices. In an X-By-Wireless implementations, connectors of this size would be obsolete.

Fig. 3. Connectors from an engine compartment wiring harness in a 1995 Dodge Neon.

3. Weight

The number of wires necessary to provide individual circuits for each component constitutes unnecessary weight. For automotive applications, this weight gain is not too significant, but in aerospace applications, these incremental differences can add up and result in reduced fuel economy.

This fuel economy aspect is most apparent in an application such as the space shuttle. It costs approximately $22,000 to put one kilogram of mass into orbit [6]. Thus, any means of safely reducing the weight of wiring harnesses is considered significant. A basic calculation shows that the weight of bare copper for a single 14-AWG wire running approximately 40 meters from the flight deck to the wing flaps weighs approximately 0.7 kg, which results in a cost of over $15,400 [7]. After multiplying by the number of such wires, the requirement for redundant or similar systems, and the number of launches for a given shuttle, it becomes clear that wires are a very expensive solution to transmit information from Point A to Point B. Fig. 4 shows a photograph of a wiring harness being installed in the Endeavour space shuttle. An X-By-Wireless implementation would significantly reduce the mass of this wiring harness and reduce launch costs.

Fig. 4. Installing a wiring harness for the Endeavour space shuttle [6].

4. Difficult to Upgrade

The increasing complexity of wiring harnesses is related to the idea that wiring harnesses are difficult to upgrade. For example, if we select an automobile that does not have an anti-theft system, we can purchase an aftermarket kit and install it. However, to do this involves running wires from a central control module to the door locks, car horn, headlights, and battery. Although this task is not exceedingly difficult, it can be a hassle to route wires to these components.

5. Fundamentally Static Layout

In typical wiring harnesses, we find that at a given point there is a specific connector available within a specific distance from the main section of the harness. Wherever the main section of the harness is routed, the component that plugs into that connector must be physically located nearby. This results in a fundamentally static layout, in which the component placement is dictated by the wiring harness.

This does not usually cause too many problems. However, to produce automobiles for both the United States and England, where the steering column is located on different sides of the vehicle, we must use significantly different wiring harnesses. In a situation where X-By-Wireless is used, the availability of a common power bus would enable a greater degree of flexibility with regards to component placement.

B. Benefits of X-By-Wireless

Although some of the benefits to an X-By-Wireless implementation are actually complements to the negatives surrounding traditionally wired system, there are others that add entirely new capabilities or features. In this section we look at both types, expanding more on how X-By-Wireless improves on the negatives and offers entirely new benefits. We can also observe trends that support the widespread growth of wireless in general.

1. Cost of Wireless Devices

The first observation we can make is that the cost of wireless devices is approaching zero. This does not imply that wireless devices are cost free, but rather their size, power consumption, and manufacturing costs are decreasing to the point where the marginal cost of choosing a wireless system instead of a wired system becomes small or possibly negative.

Bluetooth technology represents a step towards more ubiquitous wireless products. With an eventual target price of $5 USD per unit installed and a small physical size, it offers many features necessary in an X-By-Wireless implementation. It is a frequency-hopping spread-spectrum protocol that operates at the unlicensed 2.4-GHz range. It operates in small networks called piconets and provides for a large number of operations, supporting both synchronous voice communication and asynchronous data communication. It provides encrypted communications within the piconet, and is a general purpose wireless solution. Many popular applications for Bluetooth technology presently exist, such as hands-free cell phone accessories, wireless computer input devices, and short-range cell phone networking [8].

Even though the cost of existing wireless devices is presently too high for most economical X-By-Wireless implementations, we can begin taking the necessary steps to anticipate these changes. For example, protocols could be specified that are optimized for X-By-Wireless. A wireless CAN protocol that is streamlined for vehicle applications and ensures priority, security, and asynchronous data transfer would support the transition to X-By-Wireless. If these protocols are defined well in advance of the widespread use of X-By-Wireless, then by the time it is widely implemented, there will likely have been enough revisions to support the necessary bandwidth for most vehicle communications.

2. Weight Reduction

With the current state of wireless technology, we can realize weight savings by replacing a single wire with a wireless system. Measurements and calculations supporting this can be found in Chapter IV. The rationale is that in general, wireless devices have a specific amount of mass for communication up to a maximum range of distance. Alternatively, the farther apart two hardwired devices are located, the longer the wire must be that connects them, and thus the mass increases linearly per unit length.

3. Simplicity and Upgradeability

If a wiring harness in a vehicle is replaced with a wireless system, we will have a much simpler, more upgradeable system overall. This was mentioned as a problem with wiring harnesses earlier in this chapter, but now we will look at how these goals can be achieved with X-By-Wireless.

In an X-By-Wireless car, we only need two wires: one for positive voltage and one for ground. Many times, we can even use the vehicle chassis for a grounding path, which means we need only one wire. Usually, the devices are not directly connected through the ground, so we have two wires in the harness and leave the harness with the task of grounding through the chassis. Having only one or two wires in the harness produces a much smaller number of connectors and a much more flexible vehicle configuration. Devices can use common connectors, and harnesses themselves can be built in a piecewise fashion using splitters and extension cords. This technique is often used when plugging in appliances in a house or connecting devices inside a computer.

Effectively, decoupling the power and information systems results in a much more intuitive system. Tracking down wiring faults is significantly easier, simply because there much less wiring. Vehicle upgrades will not require complex wiring diagrams or splicing into existing wires because it is possible to simply add a new branching connector to power the new component.

4. Reduction of Resistive Copper Losses

Resistive power losses occur when an electrical current travels through a wire. To minimize the resistive power losses, we can either use a lower gauge wire or we can shorten the distance the current must travel. With typical vehicle wiring harnesses, we can only raise the wire gauge a certain amount, because there are physical limits on the size of a wiring harness. Fortunately, the X-By-Wireless approach can help reduce the distance that current must travel. For example the ignition system of a vehicle connects to the battery, starter, and key assembly. Operating the starter requires significant power consumption, even to turn on the starter relay. The size of the wires connected to the key assembly is evidence of this, yet they are still routed out of the engine compartment up to the steering column, adding unnecessary length to the conduction path. With X-By-Wireless, a much shorter conduction path would result, and the entire system of high-power wires would remain in the engine compartment, reducing the resistive copper losses.

5. Range

Wireless devices can have greater range than hardwired devices. If we consider the difficulty in flying a model airplane connected to the controller by a wire, or even the difficulty of using a wire to communicate with a satellite, it becomes obvious that wireless technology affords tremendous range benefits. Indeed, most existing wireless automotive applications were developed with range in mind. Wireless key chains allow doors to be unlocked before arriving at the vehicle, and radio entertainment benefits thoroughly from being able to reliably transmit over many miles.

At this time, there at no new significant or obvious benefits to be gained from the range allowed in an X-By-Wireless system. However, there may be new developments in the future which would have been exceedingly difficult to implement in a hardwired system.

6. Reliability

Taken together, many of the aforementioned X-By-Wireless benefits can be brought together to improve system reliability. In and of itself, we can see that X-By-Wireless systems are more immune to failure. With fewer wires overall, there is a lower probability of a high resistance short that can eventually drains the battery. In the course of a vehicle accident or an assembly error, if a wire is cut, any number of vehicle systems may be disabled. Because X-By-Wireless systems communicate over a common data bus, the capability for the system overall to respond intelligently to these failures is available.

Additionally, if the power bus is connected in a loop, a single break in the line will not affect the availability of power for the components. Even if a second break were to occur, locating the breaks would be trivially easy because there will be a definite location on the power bus beyond which the devices are have no power. Within components themselves, failures can be handled more elegantly and communicated to the rest of the system by making use of any extra processing power within the wireless module.

C. Conclusion

This chapter presented an overview of the drawbacks of existing wiring harnesses and the benefits we can uncover in an X-By-Wireless system. Existing wiring harnesses have become immensely complicated, use a variety of connectors, add weight, are difficult to upgrade, and have a fundamentally static layout. X-By-Wireless systems benefit from the falling cost of wireless devices, their reduction in weight, their inherent simplicity and upgradeability, the reduction of resistive copper losses, and increased range and reliability.

CHAPTER III

FEASIBILITY AND LIMITATIONS

In Chapter II, we explored many of the benefits that can be found in an X-By-Wireless implementation. If X-By-Wireless can improve so many aspects of the vehicle, then there must be reasons why we are not doing it already. Indeed there are, and present cost of wireless devices is a primary reason. However, if we assume that wireless devices continue to decrease in cost, then what should hold us back? The issues that we must respond to are interference, encryption, vital system response time, range, fusing or circuit protection, and public perception.

Taking all these issues into consideration, we still find that it is feasible to implement an X-By-Wireless system. We may have to accept certain limitations, such as minimum communication delays for vital systems, but on the whole, there is nothing to prevent full-scale wireless production. Available technologies such as the Bluetooth protocol already address concerns regarding interference and encryption, and fusing is possible through intelligent, fail-safe control of electronic switches.

A. Interference

We define interference as any situation in which two or more communication nodes fail to perform as expected. This can include either unintentional cross-talk between devices or the inability to receive a signal due to excessive noise, concurrent use of the communication channel, or poor signal strength.

In an automotive situation, if a driver turns left while using Drive-By-Wireless for steering, we should expect that the vehicle being driven turns left. If a neighboring vehicle were to inadvertently intercept the “turn left” signal, this could cause serious accidents and increase the liability for automotive manufacturers. Fortunately, the presence of a good encryption system significantly reduces the possibility of such an event.

The inability to receive a signal due to excessive noise is a common problem for devices operating in unlicensed frequency bands. For such devices, the Federal Communications Commission (FCC) regulations state “that interference must be accepted that may be caused by the operation of an authorized radio station, by another intentional or unintentional radiator, by industrial, scientific and medical (ISM) equipment, or by an incidental radiator. [9]” Thus, if an unlicensed wireless frequency is used for an X-By-Wireless system, this situation is possible.

In practice, this can happen when two different protocols use the same frequency and operate at different power levels. For example, if a Bluetooth device is held near a 2.4 GHz cordless phone, the phone can produce enough interference to render the Bluetooth capabilities useless.

OEMs can design vehicles with wireless communications in mind and avoid technologies that might cause interference. The consumer must also then be aware of the frequencies to avoid while operating the vehicle. A simpler, safer, and more expensive solution would be to license a part of the frequency spectrum specifically for X-By-Wireless applications.

B. Encryption

Whatever protocols are used in X-By-Wireless systems, there will need to be levels of security to prevent unauthorized access to or control of vehicle communications. This security is often provided through an encryption process, in which wireless signals are intentionally obfuscated before transmission occurs. The intended receiving device is able to decompose the signal into its original message, whereas other devices which receive the transmission cannot successfully decipher the message. In the Bluetooth protocol, this is achieved by using encryption keys between 8 and 128 bits in length. In addition to the message encryption, the frequency hopping pattern takes place using a pseudo-random sequence that repeats itself almost once per day [8]. The Bluetooth protocol offers significant enough encryption that it would be safe for use in an X-By-Wireless system. Any other protocol chosen for this purpose would also need to meet stringent security standards.

The drawback to using advanced encryption techniques is that it adds communication delays for processing the encryption and decryption. This delay can be minimized by using a significantly high-bandwidth protocol. If enough bandwidth is not available, then it may be necessary to restrict the X-By-Wireless implementation to systems that can tolerate longer-than-usual delays, as explained in the next section.

C. Vital System Response Time

Drivers of automobiles expect their vehicles to respond to controls in a timely fashion. If the steering wheel is turned, the tires should immediately turn as well. In the event of an accident, the collision sensor needs to respond and deploy airbags within a very small timeframe.

Fig. 5 shows a generic control system for vehicular control. The vehicle operator decides to perform an action, such as applying the brakes in an automobile. By pressing the brake pedal (controller), the anti-lock brake system is actuated. Sensors in the wheel measure the tire rotation, and will either engage or disengage the brake based upon the sensed wheel position. When the wheel ceases to rotate for a certain period of time, the driver observes that the vehicle has come to a stop and releases the brake pedal.

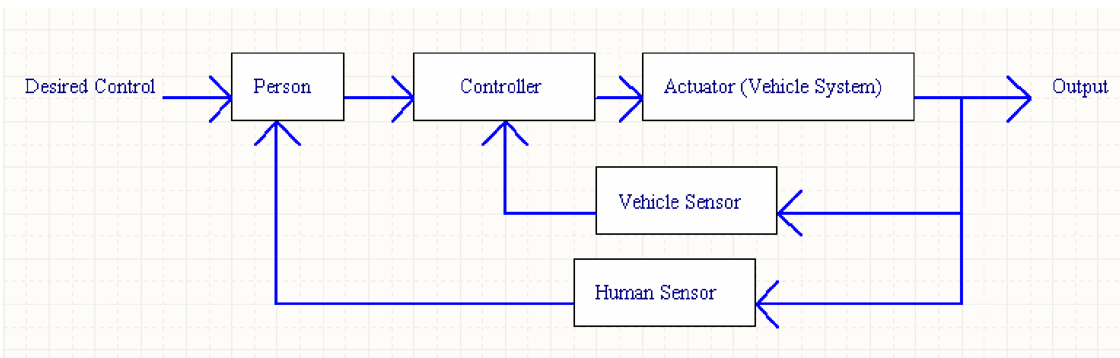

Fig. 5. Generic control system for vehicles.

Some vehicle systems that respond directly to the human control path can have reasonable delays, which we refer to as a long-time constant system. For example, if an automobile driver wants to open the power windows, it is acceptable if there is a delay longer than 500 ms. Thus, as long as the typical transmission delay of the wireless protocol is less than 500 ms, the system can safely be converted to an X-By-Wireless system. Alternatively, the collision sensor will need to respond within 15 to 20 ms [10].

If the delay is any longer, there is a safety risk to passengers, and it can actually increase the chance of injury due to late deployment. This system is classified as a short-time constant system.

Wireless protocols have different minimum transmission delays that result in different average transmission delays. On a case-by-case basis, vehicle systems should not be converted to X-By-Wireless if they are considered a vital system with a short time constant with respect to the wireless protocol time constants. The Bluetooth protocol requires at least 625 μs to exchange packets within a piconet. With a maximum of eight modules per piconet, within 500 ms we can perform over 100 packet exchanges between devices. This should be sufficient for reliable exchange of data, even allowing for interference. Thus, we can define 500 ms as a reasonable minimum transmission delay. Table I lists some different automotive systems and their classification with respect to a 500-ms transmission delay. The short-time constant systems are good candidates for a Bluetooth X-By-Wireless implementation, whereas the long-time constant systems could experience degraded performance if converted.

Table I

Automotive system classification with respect to a 500-ms transmission delay.

Large Time Constant Systems		**Small Time Constant Systems**
Door Ajar	Radio Control	Brake Sensor
Tachometer	Hazard Light Switch	Anti-Lock Brakes
Speedometer	Sunroof	Collision Sensor
Odometer	Wiper/Mist	Airbags
Fuel Level	Climate Control	Steering
Engine Temperature	Cruise Control	Throttle
Check Engine Light	Headlights	
Car Alarm	Turn Signal	
Horn	Power Mirror	
Seat Belt Warning	Rear Window Defrost	

D. Range

The lack of communication caused by a weak signal can be addressed by ensuring adequate transmission range with whatever protocol is used. For example, Bluetooth products typically transmit reliably at least 10 m. However, the Bluetooth specification provides guidelines for devices that can adjust their transmit power higher or lower based on the response of devices within its network. In any case, reliable transmission is possible as long as range limitations are considered.

In situations where the range exceeds what is needed for adequate communication, this could lead to interference for other devices that may be trying to communicate. In the Bluetooth protocol, there are 79 communication channels available, each spaced 1 MHz apart. In the event that too many piconets are trying to communicate at the same time within the same physical area, interference occurs and data throughput decreases. The frequency hopping feature of Bluetooth helps reduce the probability that a piconet will communicate on an occupied channel for very long. However, with too many piconets in range, it is likely that the next frequency hop will also land on an occupied frequency channel. For this reason, the range used needs to be well-suited for each application.

In the event that a desired protocol has too short of a range, repeater modules can be employed. This might happen if a Bluetooth X-By-Wireless system with a range of 10 m were implemented on the Space Shuttle where information will need to travel several times that distance. Ideally, it would be best to specify a protocol that did not require repeaters, but if options are limited, there is no problem with dedicating a module for relaying messages. Indeed, there may even be modules that perform their own sensing or controlling function in addition to serving as a repeater.

E. Short-Circuit Protection

A central feature of the X-By-Wireless concept is the ability to combine separate vehicles circuits onto a common power bus. The drawback of this feature is the added difficulty in providing short-circuit protection. Typical wiring harnesses route all the vehicle circuits through a few common locations called fuse boxes. Within the fuse boxes, a current-limiting fuse is placed in series with the circuit. If the maximum expected current is exceeded, the fuse physically changes to creates to form an open circuit condition. When diagnosing problems with the vehicle, it is convenient to check the fuses to narrow down the problem source. With an X-By-Wireless system, the common power bus rules out the possibility of a fuse box; the device-specific wiring only exists near the individual components. If fuses were installed in this type of system, it would be a much longer task to check for a blown fuse.

To ensure adequate protection for short-circuit conditions, we can use a more intelligent control system. If an electronic switch such as a MOSFET, IGBT, or SenseFET is used, the voltage across the switch could be measured in the on-state, and this can provide accurate current measurements. A properly scaled operation amplifier can then pass a voltage into an analog-to-digital converter. The spare processing power in the wireless device can then be used to turn of the switch in the event of excessive current.

F. User Perception

Any X-By-Wireless implementation must be considered safe to use before it finds widespread acceptance. If a vehicle operator or passenger deems something unsafe, it is likely the item in question will remain unused under normal circumstances. At this point in time people would likely be wary about riding in an automobile, boat, or airplane that used X-By-Wireless. This insecurity likely relates to personal experiences: a cell phone call dropped due to poor reception, a weak wireless network link, or analog television and radio stations that add static during adverse weather conditions. Regardless of the cause, wireless technology is often seen as unreliable.

There are many ways to combat this perception, some of which are already in place. One method is to gradually introduce wireless features until they become the norm. Owners of relatively new vehicles are accustomed to using wireless key chains to remotely unlock their door. Despite the wireless nature of this operation, the user perceives that the feature is safe and reliable; few people worry that their car door will be unlocked by unauthorized persons. If an automaker were to advertise that its next-generation vehicle would use the X-By-Wireless concept to control power windows, most consumers would have no related concerns about purchasing the vehicle.

Another way of changing user perception would be to use a licensed spectrum for the wireless communication. This would help reduce concerns about unintentional interference from nearby wireless devices. Tests could also be developed which subject vehicles to a variety of interference. If the vehicle passes these tests, then it might also bolster consumer confidence in the X-By-Wireless Implementation.

G. Conclusion

It is clear that we cannot go about blindly replacing wires with wireless communication to make an X-By-Wireless system. There are several pitfalls and limitations that must be taken into account produce a successful transition. The wireless protocol must be selected or crafted to contain measures that protect against interference or security breaches. The components communicating wirelessly must be able to anticipate and expect transmission delays for the overhead of wireless processing. The range of transmission must be suitably selected to minimize interference with other vehicles yet communicate a reasonable distance to other components. Protection from short circuit conditions must be available, and it should be implemented in such a way that it is convenient to check and reset the condition of the protection mechanism. Finally, the wireless devices must be incorporated in such a way that the end user considers it safe and reliable.

CHAPTER IV

WEIGHT REDUCTION ANALYSIS

In Chapter II, we stated without proof that X-By-Wireless implementations can provide weight savings. In this chapter, we will show theoretically and practically that this is indeed the case. Theoretically, we will make a comparison between wires of varying gauges and Bluetooth devices and show the total mass of wireless devices can be less than that of a wire. Practically, we will analyze a wiring harness from a 1995 Dodge Neon and calculate the potential weight savings from converting to a Drive-By-Wireless system.

A. Theoretical Analysis

Physical wire comes in a variety of diameters and lengths. Wire gauge is a measurement of the current carrying capability and is recorded as a number followed by the abbreviation for American Wire Gauge, such as 16 AWG. A large diameter wire is capable of carrying large amounts of current and is assigned a low value wire gauge. Conversely a small-diameter wire can carry much smaller amount of current and is assigned a high value for wire gauge. Certain systems, such as the ignition system, use higher currents than a typical vehicle electrical component, and thus are wired with low gauge wire. This results in a greater total per-unit-length wire weight for high power components. This consequence is unavoidable even in X-By-Wireless systems.

X-By-Wireless begins to show advantages over wiring harnesses when we consider the length of wire and number of wires used. A single power bus removes redundant wiring for each device, so we use fewer numbers of wires. Information no longer needs a specific wire to communicate between two points. In a regular wiring harness, when the driver of an automobile turns the key to start a vehicle, there are low-gauge wires that physically connect the key assembly to the starter of the vehicle. By removing the key assembly from the power loop, we use a much smaller amount of low-gauge, single-purpose wire.

For the theoretical analysis, we will assume the replacement of single wire used to transmit information. We neglect the mass of power wires because these would be present in both wired and wireless systems. However, if we incorporate the mass of the power bus, we can still assume that it is negligible because the effective mass per component is divided among a large number of components on a common power bus.

To begin the analysis, we take the mass per unit length of copper wire and add to it an estimated mass per unit length of insulation. The results of this approximation are given in Table II.

Table II

Estimation of copper and insulation mass for various wire gauges.

Wire Gauge (AWG)	Estimated linear density of insulation (g/m)	Linear density of copper (g/m)	Linear Density of Copper and Insulation (g/m)
18	2.0	7.32	9.32
16	3.0	11.63	14.63
14	4.0	18.50	22.50

To compare against a Bluetooth replacement, we need the mass of a Bluetooth module and the mass of a corresponding antenna. Given that there are a variety of antennas available with different capabilities, we can compare both large antennas and small antennas. If we find a favorable situation with either choice, we can be certain that all antennas between those extremes will be suitable as well. Using product information from Bluetooth suppliers [11, 12], we have the data we need as shown in Table III. Most Bluetooth modules contain a processor that is mostly used for Bluetooth-specific activities. The extra processing power can be harnessed to provide some necessary functionality, so for this exercise we will assume that the replacement system needs only the module and antenna. Furthermore, we will assume that each wire is replaced with two sets of devices, one for each end of the wire. In practice, is not likely to happen because some components, such as an automotive electronic control unit, receive input from a large number of devices. By including both sets of modules and antennas, we will find what the worst-case scenario is for a transition to Bluetooth technology.

Table III

Estimation of mass for Bluetooth modules and antennas.

Antenna	Bluetooth module mass (g)	Bluetooth antenna mass (g)	Total mass of two Bluetooth replacements (g)
gigaAnt Impexa	2.0	0.05	4.1
gigaAnt Titanis	2.0	7.5	19.0

Using the values in Table II and Table II, we can put together a graph showing the total mass of each implementation over a range of distances. Such a graph is shown in Fig. 6. As is clearly shown, the Bluetooth communication starts out with a minimum required amount of mass even for small distances, but the mass does not increase as the communication nodes become further apart. This is in contrast to a wired connection, which has practically no mass for a short distance, yet has a linearly increasing mass as we increase the distance between communication nodes.

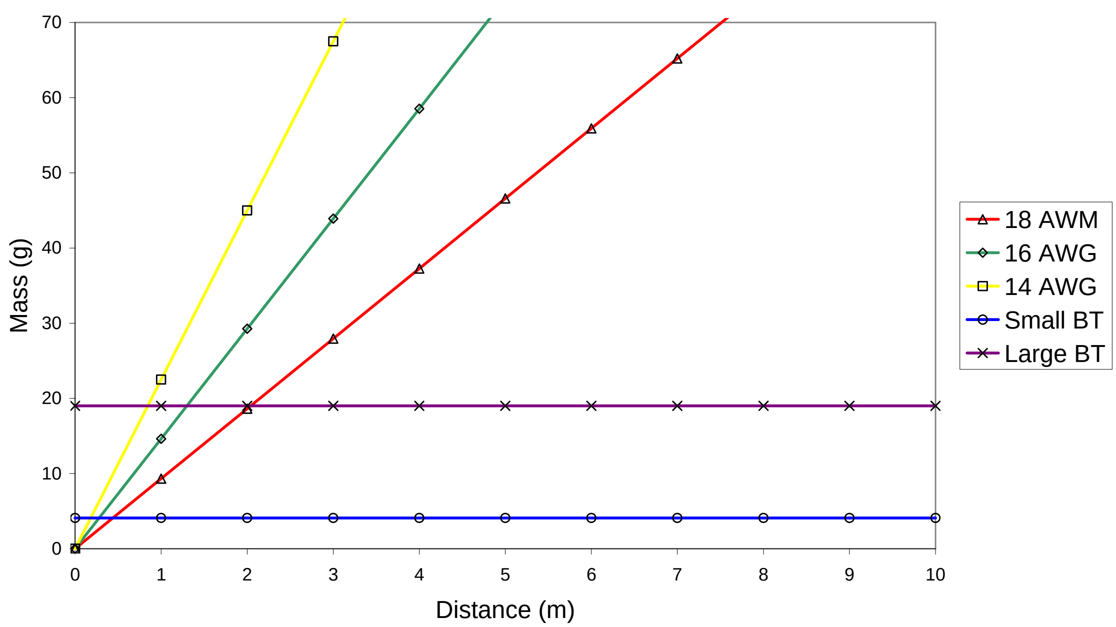

Fig. 6. Comparison of total mass for communication over a distance for copper wire of various gauges and wireless Bluetooth (BT) implementations.

We can conclude from Fig. 6 that an X-By-Wireless implementation can offer weight savings over hardwired equivalents. Specifically, at ranges less than a meter, we can observe that wires can weigh more than a Bluetooth solution. In the worst-case scenario, even after 2 m it becomes advantageous to use X-By-Wireless. Theoretically, we can support an argument for X-By-Wireless on the basis of weight reduction.

B. Case Study

The simplistic approach used for theoretical analysis is a good start, but to get a sense of certainty regarding actual weight savings, we needed to perform an analysis on an actual wiring harness. We had available a 1995 Dodge Neon that was converted into a makeshift hybrid-electric vehicle as a student project. Because the vehicle was no longer in use, it was a good candidate for performing a case study. Additionally, this vehicle lacked many features, such as power windows, power door locks, and car alarms. Thus, this analysis should represent the minimum gains that can be had in converting a traditionally wired car to an X-By-Wireless car.

1. Wiring Harness Analysis

The first step was to remove the wiring harness from the vehicle. The harness was removed in three parts: a rear section that connects to everything behind the driver seat, an engine compartment section that resided primarily in the engine compartment, and a dashboard section that included everything in between. All the non-original wiring relating to the modified hybrid vehicle components were removed and not analyzed for this case study. A photograph of the rear wiring harness after removal is shown in Fig. 7.

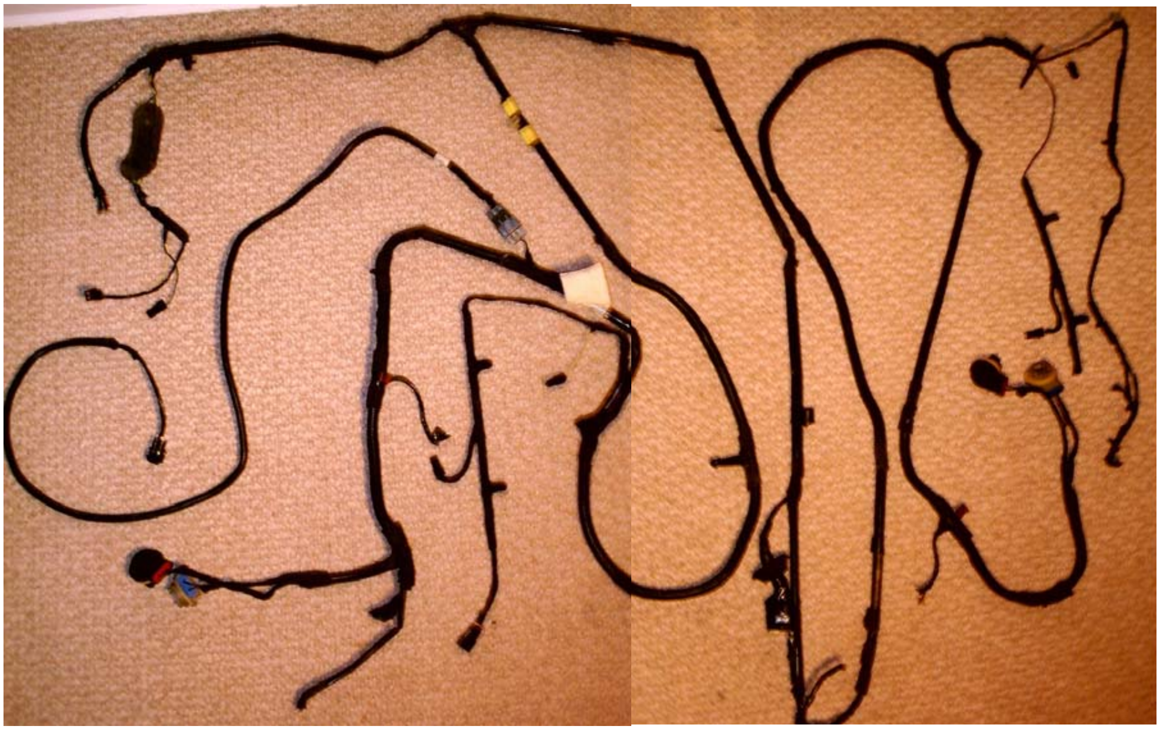

Fig. 7. Photograph of the rear section wiring harness in a 1995 Dodge Neon.

Once the wiring harness sections were removed, they were weighed and their dimensions were measured in detail. The specific measurements recorded throughout the case study can be found in Appendix A. At this point, the harness was still wrapped in tape and casing material. To get to the wires within, all the casing and tape was removed and weighed. Fig. 8 shows the exposed wiring of the rear wiring harness. Observations were recorded regarding the number and size of wires along each branch of the wiring harness. When the functionality of a particular set of wires was readily inferred, this was recorded as well. The connectors were then removed and both their mass and the mass of the wires were separately recorded.

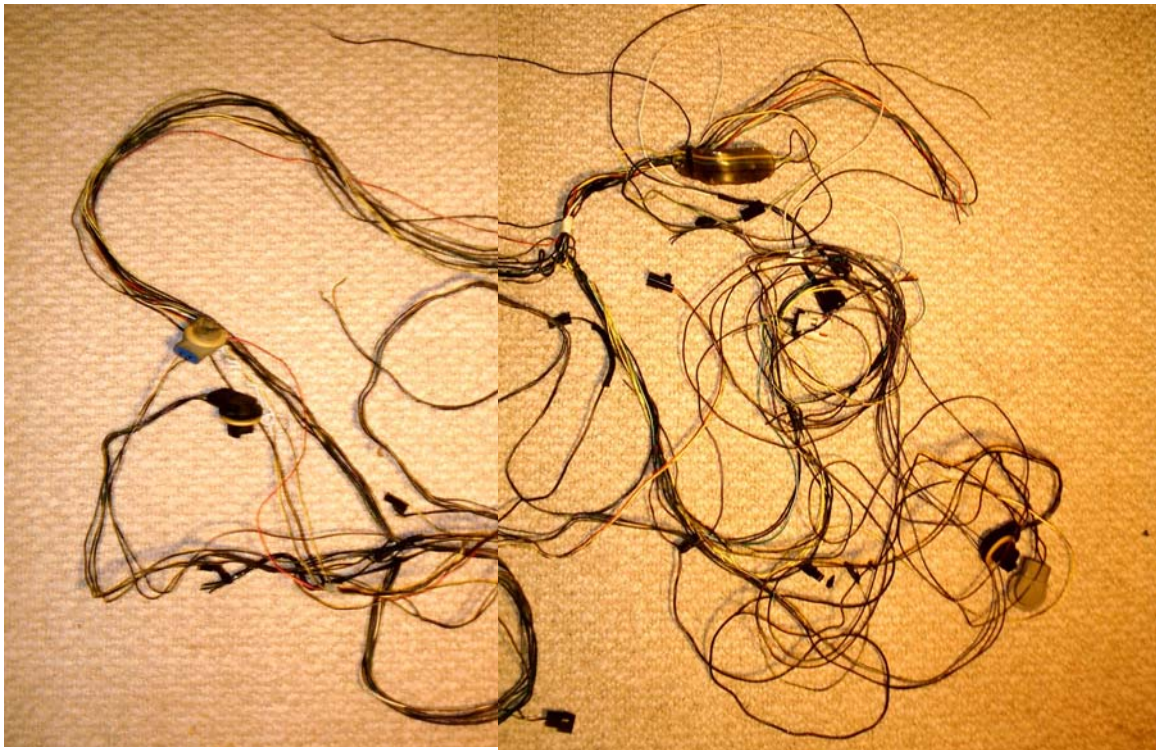

Fig. 8. Photograph of exposed wiring in the rear section of a 1995 Dodge Neon harness.

A similar procedure was likewise followed for the engine and dashboard sections of the wiring harness. At this point, all observations were made regarding the wiring harnesses. Fig. 9 shows the fully disassembled engine wiring harness.

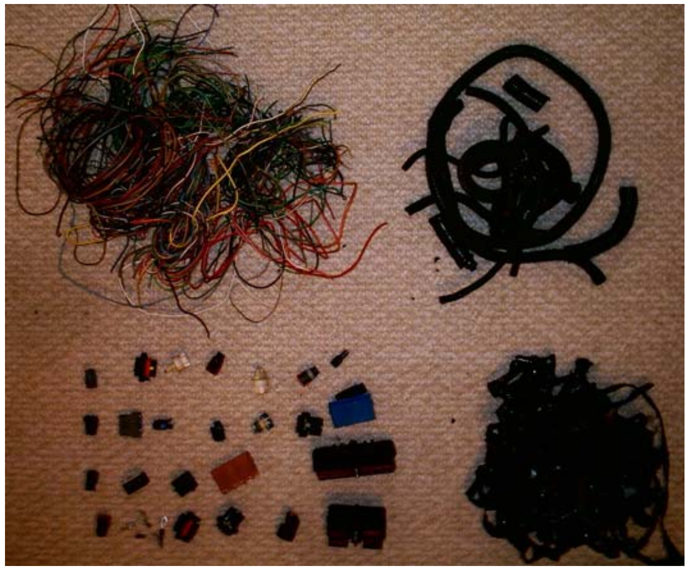

Fig. 9. Fully disassembled engine wiring harness from a 1995 Dodge Neon. Shown clockwise from top-left: wires, casing, tape, and connectors.

2. Substitution Technique

The process of analytically replacing the wiring harness with a Drive-By-Wireless system required several assumptions. First, only the wiring harness would be affected by the change; no component would need to operate any differently to deal with the wireless communication. Second, only two-wire connectors would be needed; this is rooted in the concept of using only a two-wire power bus in X-By-Wireless implementations. Third, we would route the new power bus in the same location as the old wiring harness; thus, our branch lengths will remain the same, leaving only the reduction in the number of wires. Fourth, we selected the small antenna for use in this application, because we do not need the maximum power and range provided by the large antenna. For the power bus itself, along each branch of the harness we assumed at least the same size wire and often a larger wire so as to handle expected current loads. We will also assume that the casing and tape masses do not change. Finally, we assumed that all wires could be safely replaced with a wiring harness; we assumed that all vehicle components have long enough time constants with respect to the wireless transmission delays.

3. Substitution Results

The substitution of X-By-Wireless using Bluetooth devices would require the use of 55 wireless modules for the entire vehicle. The mass comparison between wireless and hardwired systems is provided in Table IV. A graphical view of these results are provided in Fig. 10

Table IV

Numerical comparison between the mass (in grams) of hardwired and X-By-Wireless implementations in a 1995 Dodge Neon. Hardwired values have a white background and X-By-Wireless values have a gray background.

	Rear		**Dash**		**Engine**		**All**	
Connectors	156	190	354	180	539	330	1049	700
Wire	553	249	1658	238	1361	226	3572	713
Tape	241	241	184	184	213	213	638	638
Casing	213	213	57	57	170	170	439	439
Total	**1162**	**892**	**2254**	**659**	**2282**	**938**	**5698**	**2490**

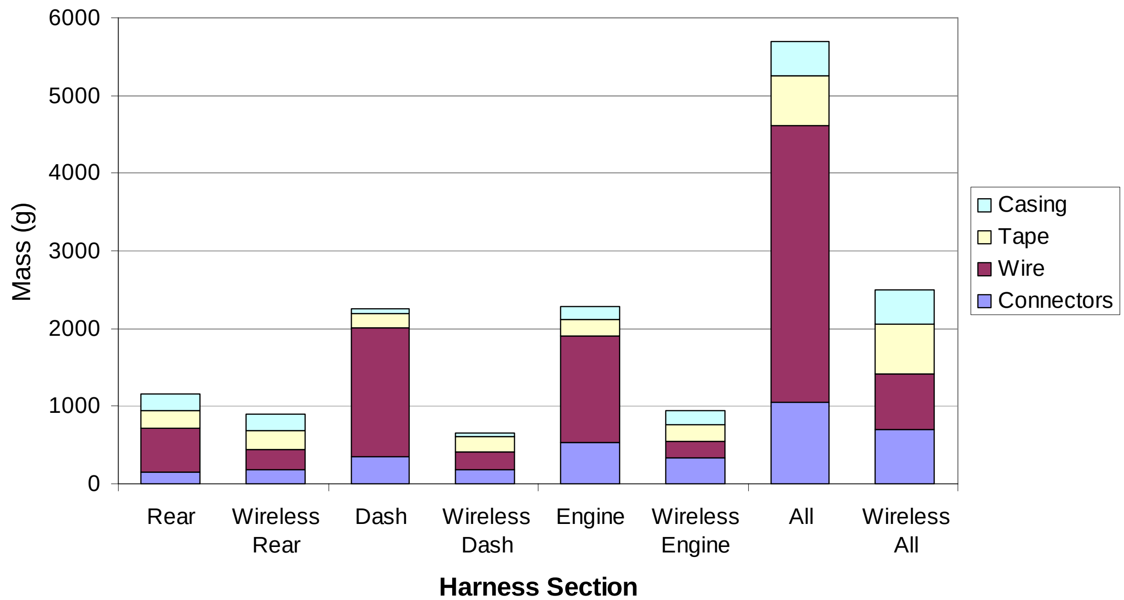

Fig. 10. Graphical comparison between the mass of hardwired and X-By-Wireless implementations in a 1995 Dodge Neon.

In Table IV and Fig. 10, the mass of the Bluetooth modules is lumped into the wire classification. We can observe that the X-By-Wireless implementation reduces our total wiring harness mass by 56%, and the total wire mass alone is reduced by 80%. The dashboard section of the wiring harness, which is the most electrified, information-rich part of the harness experienced a 70% weight reduction overall and an 86% reduction in wire weight.

Furthermore, even if each of the 55 Bluetooth modules used the largest possible antenna, this would result in a total mass increase of about 400 grams over the situation using the smallest antenna; the mass of the wiring harness would still be reduced to half of its original value. This case study demonstrates that we can reasonably expect an X-

By-Wireless system to weigh anywhere from 50% to 80% less than a comparable hardwired system.

C. Conclusion

In this chapter, we verified our claim that X-By-Wireless systems can have a much smaller mass than traditional wiring harnesses. Through a basic theoretical analysis we showed that the concept of reducing mass by using wireless technology is plausible. We then performed a case study involving an actual wiring harness so as to develop realistic expectations regarding practical implementations of X-By-Wireless. Through the case study, we found that mass reduction in an X-By-Wireless system can reduce wiring harness mass by more than 50% for automotive applications.

CHAPTER V

WIRELESS SYSTEM CONTROL CIRCUITS

X-By-Wireless offers a wide range of benefits to vehicles. We can recognize reductions in mass and copper losses while benefiting from the inherent simplicity and increased flexibility and upgradeability. However, if there is no practical means of implementing such a system, then these benefits remain unattainable and this research becomes a mere academic exercise. Fortunately, a circuit can be devised that allows the aforementioned benefits while addressing such concerns as interference, encryption, and overcurrent protection. This chapter describes such a circuit and its variants.

A. Proposed Solution

To implement an X-By-Wireless system, we first need an acceptable wireless protocol. The protocol must allow for sufficient communication range, data throughput, interference resistance, security, and low-power operation. It should also be affordable, but considering the general trend toward lower wireless costs, affordability should not be a primary concern at this time. In addition to a suitable wireless protocol, we will need a means of disrupting overcurrent conditions. Lastly, we will need to verify manufacturability of the proposed solution so that it can cheaply and easily be mass-produced.

1. Bluetooth

The Bluetooth protocol is a workable selection for X-By-Wireless. Operating at between 2.400 GHz and 2.476 GHz, it supports interference resistance by employing a pseudo-random frequency hop over 76 frequency channels. The communication range of Bluetooth devices is typically between 10 to 20 m, although the protocol does support a 100 m range as well. Security is made possible through anywhere between 8- and 128-bit encryption [8]. Bluetooth devices are also intended for low-power applications, as evidenced by their short range and typical application in small electronic devices. Regarding affordability, full-fledged Bluetooth modules presently cost about $60 USD. However, the protocol was initially created with the intent that it would eventually cost only $5 USD to add Bluetooth capability to a device. Many single-purpose consumer Bluetooth devices, such as hands-free headsets, presently cost as little as $35 USD retail.

Although Bluetooth piconets can only contain eight Bluetooth devices, a single device can connect to multiple piconets. Regarding the networking technique, we have two extremes architectures. One type would have a multi-tiered-hierarchy in which all commands are routed through a single master module, whereas the other would consist of autonomous piconets among only those devices which might need to communicate with each other. More realistically, we might have a combination of the two, in which piconets are grouped logically and the vehicle electronic control unit is a part of every piconet. This reduces message transmission delay because devices only receive or transmit information relative to their piconet, yet it allows inter-piconet communication via the electronic control unit.

Although we can use Bluetooth as a workable solution, it is not the ideal solution. It would be preferable to have a more streamlined protocol for relaying messages of varying priority, much like the CAN protocol. As it stands, the Bluetooth protocol is exceedingly general-purpose, and many of its higher-level features, such at the telephony protocol and synchronous connection-oriented links, are simply not necessary in a vehicle application. The ideal situation would be to have a type of wireless CAN protocol which combines the security and interference protection of Bluetooth and the priority-based messaging scheme of CAN, while removing unnecessary elements of each. If the new protocol were backed by a licensed or otherwise dedicated range of wireless frequencies, this would certainly help ensure more reliable wireless communications.

2. Electronically Sensed Fusing

In the event of a short circuit failure in any vehicle component, it is desirable to disrupt the flow of power to the component until it can be replaced or repaired. Typically this occurs with a fuse that mechanically creates an open circuit by melting a small section of wire. Because the power bus in an X-By-Wireless system prevents us from having one or two conveniently-located fuse boxes, we must forego fuses that require mechanical replacement.

Alternatively, we can create a simulated fuse through carefully controlled electronic switches. Insulated-Gate Bipolar Transistors (IGBTs) and Metal-Oxide Semiconductor Field Effect Transistors (MOSFETs) are two such electronic switches. IGBTs and MOSFETs are three terminal devices in which a small input voltage on one terminal allows electric current to flow through the other two terminals. Removing the small voltage prevents current flow between the other two terminals. However, even in the on state, there is still a voltage drop across the conducting terminals. For the IGBT, this voltage drop is relatively independent of the controlling voltage, and even for small currents there is a voltage drop. Conversely, for a MOSFET, the voltage drop highly depends on both the controlling voltage and the current conducted. This represents a fundamental different in the operation of the devices. Specifically, an IGBT is a minority carrier device, whereas the MOSFET creates a conduction channel. Additionally, there is a special type of MOSFET called a SenseFET which is designed for ease of current sensing. A graph of current vs. voltage drop for varying control voltages for an IGBT is given in Fig. 11, and a similar graph for a MOSFET is given in Fig. 12.

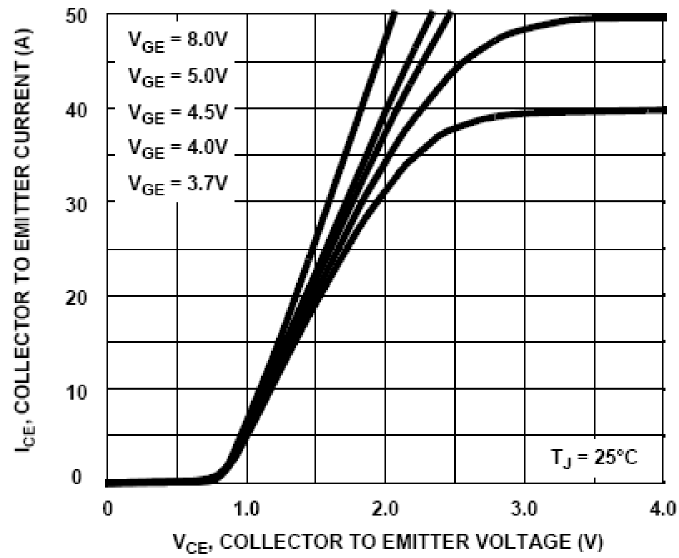

Fig. 11. Conduction current vs. voltage drop at varying IGBT control voltages [13].

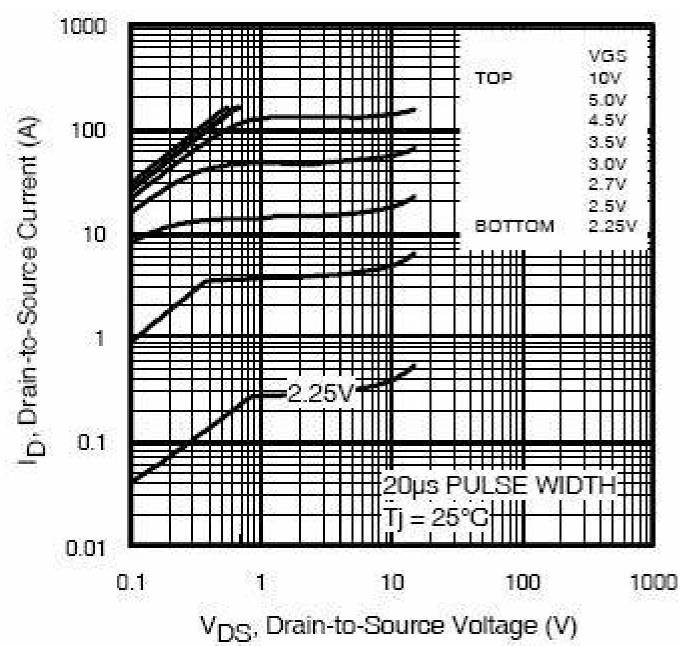

Fig. 12. Conduction current vs. voltage drop at varying MOSFET control voltages [14].

In automotive applications, the minimum voltage drop in an IGBT makes it a less-than-ideal solution for today's low-voltage systems. If OEM manufacturers begin regularly using higher system voltages, then IGBT might be a good choice, as they are optimized for high-voltage and low-frequency operation. The low on-resistance of a MOSFET makes it ideal for low-voltage systems, such as the existing 12 V network presently found in most vehicles.

Regardless of which switch type is used, the voltage across the terminals can be measured and amplified. If the voltage exceeds a preset maximum threshold, we can assume that a short-circuit condition exists, turn off the switch, and wirelessly communicate the situation to other devices. A common-mode difference amplifier circuit can be employed to measure the voltage and reproduce an appropriately scaled signal [15]. This signal can be measured by an analog-to-digital converter and then supplied to the control processor within the wireless module. When the processor determines that the maximum voltage threshold is exceeded, the switch is turned off; and the switch can later be re-enabled via wireless communication to the processor.

The wireless device itself must be able to remain on even when the switch is turned off. To facilitate this and ensure overcurrent protection within the device itself, each wireless device should have its own small protective fuse. In the event that the fuse for the wireless module itself causes an open-circuit condition, there can be a small battery on board that allows only the wireless processor to operate. This will allow easy diagnosis of the blown fuse, as the wireless device can communicate a distress signal for a period of time even without a connection to the vehicle power bus. Additionally, because we use an electronic switch that requires positive voltage to turn on, we have designed the circuit for fail-safe operation; if the wireless fuse blows, the electronic switch is forced into the off position.

A complete diagram of the proposed solution is given in Fig. 13. A much simpler version of the diagram showing only the major components and connections is given in Fig 14.

The presence of the ADC also allows us to use the module for sensing purposes. By including a second op amp circuit, we can measure the voltage across devices like fuel-tank sensors and engine-temperature sensors. A technique for measuring the voltage across these passive devices is shown in Fig. 15. Once these measurements are made, they can be converted into a digital signal and then be wirelessly broadcast to other devices. If necessary, a circuit can fully perform both duties of switch control and component sensing.

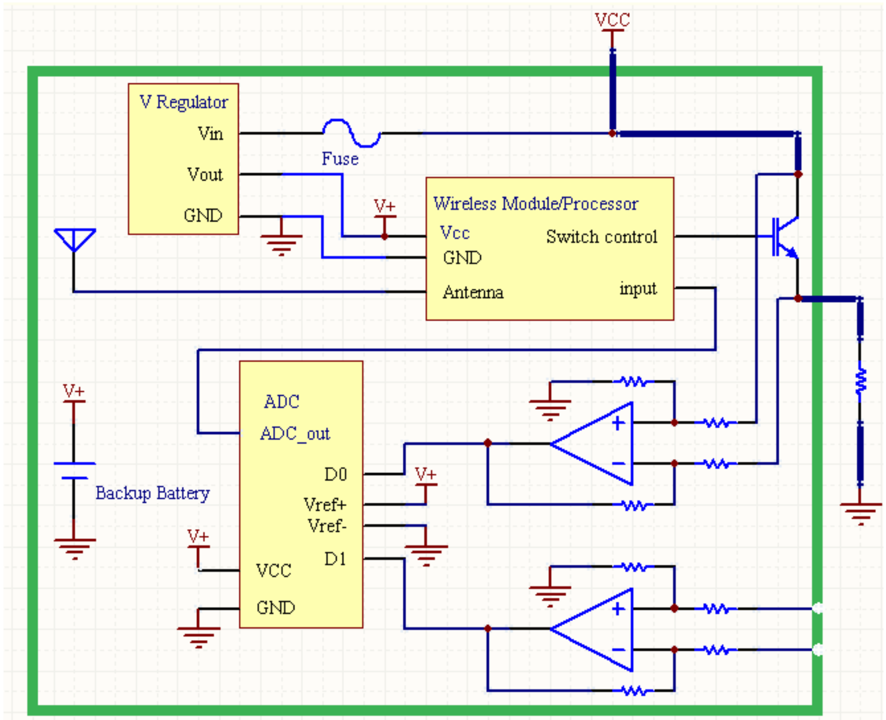

Fig. 13. Complete diagram for proposed X-By-Wireless circuits.

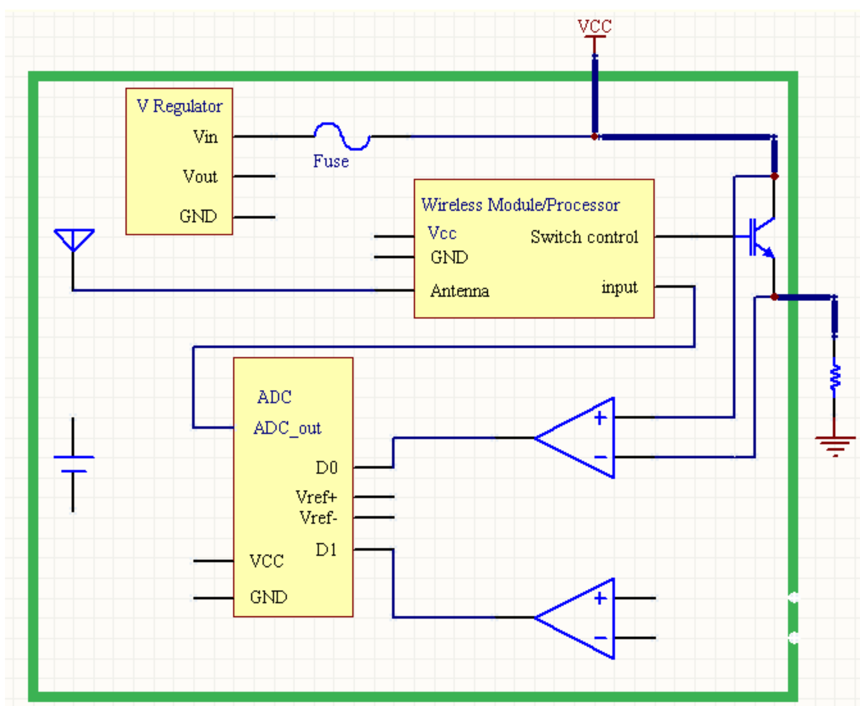

Fig. 14. Simplified diagram for proposed X-By-Wireless circuits.

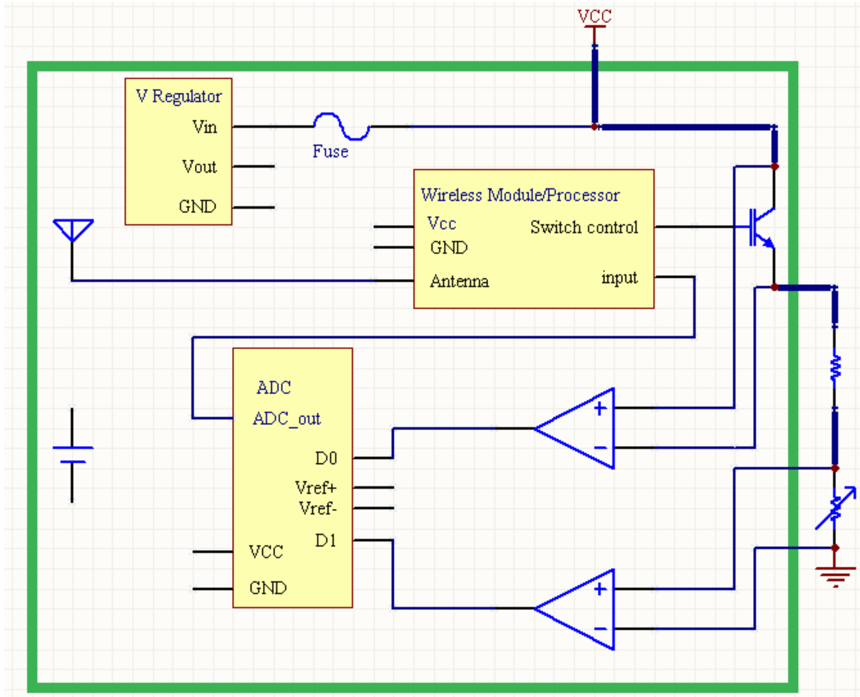

Fig. 15. Simplified diagram for X-By-Wireless circuit with sensing capabilities.

3. Manufacturability

In addition to designing a functional circuit, we need to ensure that it provides a generic enough solution for a range of applications. As specified before, the power bus voltage should dictate what type of electrical switch is used; however, beyond that, the circuit can be identical for a range of applications. If the circuit is designed around a 20-A switch, we can program the processor to shut off the switch if any current value between 0 and 20 A is exceeded. For example, we can have identical devices that protect a 5-, 10-, and 20-amp device. The only differentiating factor between them is in the software. For greater accuracy, different op amp resistors could be used for different maximum current limits, but this too is a trivial difference between circuits. In general, we can have mass-produced devices for each current rating, much like regular automotive fuses are presently produced. Additionally, to save on electronic switch costs, we can also a have a “sensor-only” device type.

B. Conclusion

In this chapter, we looked at how an X-By-Wireless system might actually be implemented. We looked at different protocol features and selected Bluetooth as a suitable wireless protocol, although it is certainly possible that a more adequate protocol might be devised in the future. The mechanism of short-circuit protection was described and guidelines for electronic switch selection were presented. Finally, we addressed concerns about mass-production and concluded that a finite number of modules can be designed that emulate the current protection ratings offered by existing fuses.

CHAPTER VI

SUMMARY AND FUTURE RESEARCH

In this chapter, we review the main ideas behind the X-By-Wireless research and address what the next research steps might involve.

A. Summary

X-By-Wireless is a new paradigm in vehicle communication systems. Decoupling power and information completely allows for new degrees of flexibility with respect to how information is transmitted. If we select a wireless communication method, we can adopt an entirely new approach to vehicle inter-component communication. Furthermore, we can reduce both short-term and long-term costs because assembly and maintenance is easier, and reduced mass can decrease operating costs for weight-sensitive applications.

Before an X-By-Wireless system is implemented, however, careful choices should be made with respect to the wireless protocol used, the switch type selected, and which systems can be safely converted to wireless. Bearing in mind any limitations imposed by those selections, there are no technological barriers that prevent a successful system design. To that end, a circuit was presented that can effectively meet the X-By-Wireless qualifications while being generic enough allow for mass production and operational variety.

B. Contribution of This Research

This research has explored a new approach to vehicle wiring. It defined the X-By-Wireless concept and established the rationale behind the concept. The problems concerning existing wiring harnesses were considered in light of the possibilities of an X-By-Wireless system. Indeed, many of the drawbacks were not even considered as drawbacks until compared side-by-side with X-By-Wireless. The problems concerning X-By-Wireless were also examined and potential solutions were devised.

An analysis was also performed to confirm that mass reductions were possible for an X-By-Wireless system. This analysis consisted of both a theoretical wire vs. Bluetooth situation and a case study involving an actual wiring harness. The result of this analysis indicates that there will almost certainly be mass-reduction benefits in the majority of X-By-Wireless applications.

This research also investigated how a practical X-By-Wireless device might be constructed. To that end, we presented a circuit capable of addressing many of the concerns in implementing an X-By-Wireless system. The circuit is able to turn on and off electrical component loads, provide short-circuit protection, function as a voltage sensor, and communicate wirelessly with other devices. Issues such as mass production manufacturability were also addressed as well.

C. Future Research

Although this thesis asserts that we have the technology to implement X-By-Wireless, there are many optimizations that can be researched. As indicated previously, there is much to be desired with respect to a suitable wireless protocol. Bluetooth can perform the task, but its method of operation is not streamlined for this purpose. It would be useful to research the development of a more fitting protocol that retains or improves upon the beneficial aspects of Bluetooth while incorporating features that would be advantageous to an X-By-Wireless system.

In addition to developing a protocol specification, the proposed circuit solution can be optimized as well. A voltage regulator was used to provide the reduced voltage needed for the ADC and processor. However, these devices add mass are inefficient, produce heat, and take up local volume. It might be more advantageous to have a low-voltage wire on the power bus which the X-By-Wireless devices can use as a voltage source. In addition, if the fuse for the wireless circuit blows, there still exists a high-resistance positive voltage path through the op amp sensor. For reliability reasons, it might be worthwhile to instead to sense the voltage across the fuse and the switch, even though this could affect the voltage reading, particularly is a low-on-resistance MOSFET switch is used.

Another research step could involve actual construction and testing of an X-By-Wireless system. There may be issues not yet addressed that could become more significant for an actual implementation. For example, in an automobile, the electrically conductive nature engine block may prevent wireless signals from effectively passing through it, in which case we have to take into account line-of-sight around such vehicle components. In another case, there may simply be too much interference in unlicensed frequency bands, necessitating the need to use a reserved frequency for successful operation.

Finally, research could be performed on novel systems that specifically leverage the new capabilities introduced in an X-By-Wireless communications system. It may be possible to create devices that store power locally, eliminating the need for connection to the power bus. For example, an eddy-current brake can be activated by a small amount of energy. If this energy is captured during a previous braking cycle, and if an X-By-Wireless system is in place, then the eddy-current brake can be made completely wireless by removing it from the power bus [16]. There are likely a number of other system components that can be implemented much more efficiently when X-By-Wireless is the predominant communication system.

D. Conclusion

The X-By-Wireless concept has much to offer over conventional wiring harnesses. As the cost of wireless devices approach zero, it becomes possible to use wireless technology not only where it is absolutely necessary, but also in applications where a hardwired solution is traditionally used. Instead of using physical wires by default, an X-By-Wireless approach uses wireless by default. When viewed from this perspective, we can recognize not only the benefits inherent in such a system, but also new problems that must be addressed. Successfully addressing the problems creates long term solutions that allow X-By-Wireless to become the *de facto* standard for vehicle communications.

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APPENDIX A

WIRELESS SUBSTITUTION ANALYSIS

For the case study in Chapter IV, the 1995 Dodge Neon wiring harness was analyzed in three parts: rear, dash, and engine compartment sections. The actual mass of these harnesses is recorded in IV. This appendix contains the data used to approximate the mass and perform the subsequent wireless substitution; thus, there are variations in the measured wire mass and the approximated wire mass in this analysis The linear density of 18-AWG wire (including insulation), was 0.0932 g/cm, and the linear density of 14-AWG wire (including insulation) was 0.215 g/cm. For each harness, the tables show the length and mass of each section, along with the number of 14-AWG and 18-AWG strands it contains. The length information is staggered to show the node hierarchy. The wireless substitution tables show how many wires of each gauge are needed in the power bus and the mass of the Bluetooth device at each node. Where appropriate, 12-AWG wire is used (at 0.344 g/cm) in place of several 14-AWG wires. Also, the ignition system was specifically rewired to minimize the number of high-power wires leaving the engine compartment. Table V shows the breakdown of the rear section of the harness, and Table VI shows the resulting masses from wireless substitution in the rear harness.

Table V

Detailed breakdown of rear wiring harness in a 1995 Dodge Neon.

#18AWG	#14AWG	Length of wire sections (cm)											Mass (g)
25	6	55	*to dash harness*										199.1
6	1		22										17.0
28	7		6										24.7
6	0			28									15.7
33	6			5									21.8
0	2				17								7.3
4	0				55								20.5
35	6				20								91.0
2	0					83							15.5
37	6					20							94.7
14	2						25						43.4
26	1						10						26.4
46	0						30						128.6
2	0						45						8.4
27	1						45						122.9
0	3							22					14.2
3	1							29					14.3
0	3							29					18.7
19	5							10					28.5
2	0								22				4.1
2	0								35				6.5
6	0								22				12.3
13	0								100				121.1
4	0									30			11.2
13	0									18			21.8
2	0										18		3.4
9	0										34		28.5
2	0											78	14.5
2	0											40	7.5
2	0											31	5.8
2	0											13	2.4
3	0											27	7.5
													1159.2

Table VI

Detailed breakdown of rear harness wireless substitution in a 1995 Dodge Neon.

#18AWG	#14AWG	BT Mass (g)	Total mass (g)
	1		5.2
	1		5.4
1		2.1	3.0
1		2.1	3.5
1		2.1	2.6
	1		8.6
	1		25.8
	1		6.5
	1		7.7
	1		4.3
1		2.1	4.4
1		2.1	4.9
1		2.1	3.3
1		2.1	16.1
	1		3.9
1		2.1	2.8
	1		6.9
1		2.1	4.1
1		2.1	2.9
	1		19.4
	1		6.5
	1		25.8
	1		14.0
	1		4.3
1		2.1	4.4
1		2.1	4.9
1		2.1	3.3
	1		3.9
	1		14.2
1		2.1	3.3
1		2.1	4.0
1		2.1	6.1
1		2.1	2.8
	1	2.1	4.0
	1	2.1	5.8
			248.5

Table VII shows the breakdown of the rear section of the harness, and Table VIII shows the resulting masses from wireless substitution in the rear harness.

Table VII

Detailed breakdown of dash wiring harness in a 1995 Dodge Neon.

#AWG18	**#AWG14**	**Length of wire sections (cm)**									**Mass (g)**
27	4	18									60.8
8	1		13								12.5
3	2		17								12.1
31	10		30								151.1
9	0			15							12.6
27	10			20							93.3
25	6				20	*to engine*					72.4
17	4				10						24.4
10	3					25					39.4
7	1					25					21.7
9	1						45				47.4
6	0							8			4.5
11	1							105	*to rear*		130.2
46	15		15								112.7
25	1			30							76.3
2	0				12						2.2
23	0				15						32.1
17	0					140					221.7
15	0					30					41.9
6	0					60					33.5
29	16			18							110.6
5	8				6	*steering col. & ingnition*					13.1
0	1					11					2.4
2	5					15					18.9
3	2					27					19.2
22	10				38						159.6
6	0					8					4.5
16	10					15					54.6
4	4		50								61.6
0	4			10							8.6
4	0			32							11.9
											1667.9

Table VIII

Detailed breakdown of dash harness wireless substitution in a 1995 Dodge Neon.

#18AWG	#14AWG	#12AWG	BT mass (g)	Total mass (g)
	1		2.1	6.0
	1		2.1	4.9
	1		2.1	5.8
		1		10.3
	1		2.1	5.3
		1		6.9
		1		6.9
		1		3.4
	1		2.1	7.5
	1			5.4
	1			9.7
	1		2.1	3.8
	1		2.1	24.7
		1		5.2
	1			6.5
1			2.1	3.2
	1			3.2
	1		2.1	32.2
	1		2.1	8.6
	1		2.1	15.0
	1			3.9
	1			1.3
	1		2.1	4.5
	1		2.1	5.3
	1		2.1	7.9
	1			8.2
	1		2.1	3.8
	1		2.1	5.3
	1			10.8
	1		2.1	4.3
	1		2.1	9.0
			37.8	238.4

Table IX shows the breakdown of the rear section of the harness, and Table X shows the resulting masses from wireless substitution in the rear harness.

Table IX

Detailed breakdown of engine wiring harness in a 1995 Dodge Neon.

#AWG18	**#AWG14**	**Length of wire sections (cm)**											**Mass (g)**
25	6	55	*to dash harness*										199.1
6	1		22										17.0
28	7		6										24.7
6	0			28									15.7
33	6			5									21.8
0	2				17								7.3
4	0				55								20.5
35	6				20								91.0
2	0					83							15.5
37	6					20							94.7
14	2						25						43.4
26	1						10						26.4
46	0						30						128.6
2	0						45						8.4
27	1						45						122.9
0	3							22					14.2
3	1							29					14.3
0	3							29					18.7
19	5							10					28.5
2	0								22				4.1
2	0								35				6.5
6	0								22				12.3
13	0								100				121.1
4	0									30			11.2
13	0									18			21.8
2	0										18		3.4
9	0										34		28.5
2	0											78	14.5
2	0											40	7.5
2	0											31	5.8
2	0											13	2.4
3	0											27	7.5
													1159.2

Table X

Detailed breakdown of engine harness wireless substitution in a 1995 Dodge Neon.

#18AWG	#14AWG	#12AWG	BT mass (g)	Total mass (g)
	1			11.8
	1		2.1	6.8
	1			1.3
	1		2.1	8.1
	1			1.1
	1		2.1	5.8
	1		2.1	13.9
		1		6.9
1			2.1	9.8
		1		6.9
		1	2.1	10.7
	1		2.1	4.3
	1		2.1	8.6
1			2.1	6.3
		1		15.5
	1		2.1	6.8
	1		2.1	8.3
	1		2.1	8.3
		1		3.4
1			2.1	4.1
1			2.1	5.4
	1		2.1	6.8
	1			21.5
	1		2.1	8.6
	1			3.9
1			2.1	3.8
	1		2.1	9.4
1				7.3
1				3.7
1				2.9
1				1.2
1				2.5
				225.7

The final row in Table VI, Table VIII, and Table X indicate the total mass needed to replace wires with wireless in the rear, engine, and dash sections of the harness. These correspond to the wireless “wire” masses of 249 g, 238 g, and 226 g listed in Table IV.

VITA

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