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Safe-by-Wire: The Leading Edge in Vehicle Airbag Control

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ABSTRACT

Consumer and safety requirements are increasing the number of airbags per vehicle that need to be controlled in an intelligent manner. Smart air bag controllers can determine which bags are fired and at what times and which sequences in order to increase occupant survivability and reduce the cost of airbag replacement for repairable vehicles.

Some vehicles already have an excess of 10 air bag systems and clearly a need for computer control to implement advanced features exists. The critical need to maintain the current high reliability factors in terms of misfiring and unintentional deployment must be maintained and perfected while adding more features.

The Safe-by-Wire consortium has been formed to address these concerns and they have designed a new bus protocol. This article will examine some of the issues regarding air bag systems and the Safe-by-Wire protocol specifically.

INTRODUCTION

Airbags have been deployed in over 2 million crashes saving thousands of lives and unfortunately, taking a few. Much knowledge has been gained in the last ten years from these crashes. This knowledge is being used to develop restraint systems with additional airbags and features to save more lives and reduce the severity of injuries and deaths caused by the system.

Current airbag systems consist of a crash sensor, two airbags and some sort of system to create an explosion to inflate this airbag quickly. The airbag must inflate in about 20 msec and quickly deflate about 300 msec after the deployment. The airbag expands at a speed of 150 to 200 mph. At 55 mph, a car travels 1.6 feet in 20 msec.

Sensors are designed to deploy the airbags at crashes at speeds as low as from 10 to 16 mph depending on whether seat belts are being worn. Airbags can therefore be deployed in crashes that fatalities are not always expected and their worth will be in reducing or preventing serious injuries. The National Highway Traffic Safety Administration (NHTSA) claims air bags reduce fatal injuries by 11 percent for drivers and 13 percent for adult passengers. It is considerably more difficult to gauge the injuries mitigated or prevented altogether.

Airbags can kill children or small adults when they are deployed. Airbags are most effective if they are applied to a person's torso at a distance of about 10 inches. Small people such as children usually have the airbag applied against their neck and head creating a dangerous situation. Pregnant women also are in danger as they may be unable to provide this distance. Another problem is people out of position in the seat.

Multiple airbags provide solutions to these problems but they need sophisticated electronic control of the sensors and deployment devices. Airbags are now located in the doors and roof columns to provide protection against side impacts. Additional crash sensors to detect these side crashes and immediately deploy the airbags are needed. Inflatable seat cushions and floor mats are being developed to decrease the occupants' injuries.

It is possible to deploy a passenger airbag only if the seat is occupied. The problem is a child does not then get airbag protection in a crash. A better system is if the passenger is weighed and the appropriate size airbag is deployed in a crash scenario. Additionally, different size airbags can be deployed sequentially to increase the protection for vehicle occupants. Out of position occupants can be detected and the airbag deployment scheme can then be compensated.

It becomes clear that additional computing power is needed to provide smart airbag deployment with a fast and reliable network to connect the restraint system components together. Current systems such as CAN, LIN or wireless are not reliable, fast or deterministic enough. The Safe-by-Wire consortium has been formed to address these concerns and a new bus protocol has been designed. Silicon is available in sample quantities with production soon. Many firms are developing advanced occupant safety systems using Safe-by-Wire. This paper will examine some of the issues regarding air bag systems and the Safe-by-Wire protocol specifically.

SAFE-BY-WIRE TECHNICAL PRIMER

The Safe-by-Wire **(SbW)** protocol has features taken from preceding protocols including CAN. The specification describes the Physical Layer, Data Link Layer and part of the Application layer.

A SbW system is a Master-slave configuration and includes devices to detect a crash and deploy airbag(s).

SAFE-BY-WIRE BUS ARCHITECTURE

The Safe-by-Wire Bus (SbW)

The bus is a two wire differential pair that has three data levels and a power level. The differential voltage level varies between 11 and 0 volts. The SbW bus uses a recessive and dominant bit scheme similar to the CAN bus. This is used to enable a slave to put its data on the bus rather than to determine priority as in the CAN bus. Power is distributed from the master to the slaves via the SbW bus.

The SbW specification allows for a separate Deployment and Sensor bus but most current designs use a combined deployment and sensor bus.

The specification also allows various bus topologies such as parallel, daisy-chain, tree and ring but the parallel mode is most often used in practical designs.

Figure 1 shows a simple example of a SbW network. Note the separate Sensor and Deploy busses and the twisted pair wires.

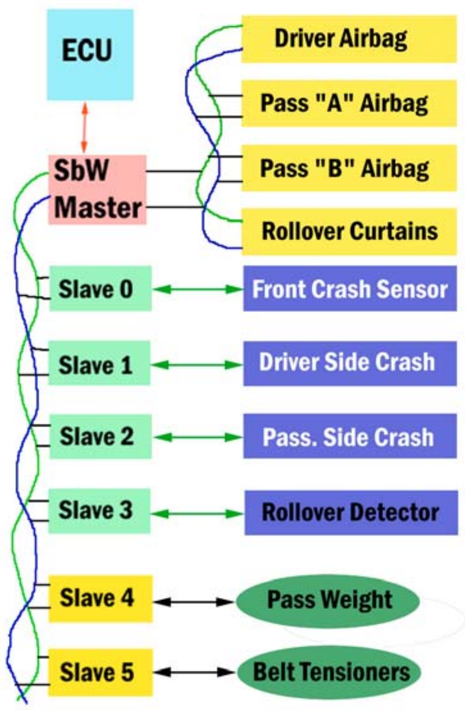

Figure 1 Example Safe-by-Wire Network

Master

The master is called a Sensing and Diagnostic Module (SDM) in the specification. The master controls all bus action and addresses the slave devices. The master sets up a frame that the slaves impress their data in the appropriate bit positions. This greatly speeds up the communication rate as there are no complicated send and receive bus frames. The reply is contained in the second half of the requesting frame.

Slaves

Slaves are connected to deployable devices such as an airbag and to input sensors such as crash detectors. Slaves are programmed with an address in non-volatile memory that the master can use to address the slaves.

Sensors

Sensors provide the master with crash data. There are two types of sensors: dynamic and static. Dynamic sensors are typically side and front impact sensors that have high data rates. Static sensors have low update rates providing information to the master with a lower priority including occupant information such as seat belt use, occupant weight and position.

Deployment Devices

Deployment devices contain a pyrotechnic device called a squib which is activated by an electrical charge. This squib ignites a chemical agent (sodium azide) that creates a gas (nitrogen) that rapidly inflates the airbag. A squib is similar to a blasting cap used to detonate dynamite. A squib is activated by discharging a capacitor into it that was charged via the SbW bus. A two stage airbag contains two squibs to provide two levels of airbag protection. Figure 2 is a one stage airbag unit from a steering column. Also shown is the rotary unit that connects the airbag on the steering wheel to the chassis allowing it to rotate. This is does not contain a slip ring and brushes but a continuous ribbon cable for reliability.

Figure 2 Steering Column Driver Airbag Module

BUS SIGNALS

The bus is a differential pair and communication between the master and the slaves is by both voltage and current levels. The bus is recessive/dominant. Lower voltages are dominant. Bus devices will use the recessive/dominant scheme to detect bus collisions and impress data into frames created by the master. Figure 3 shows the four levels of differential voltage on the bus.

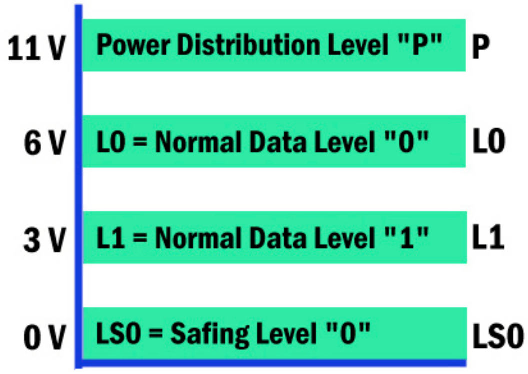

Figure 3 Differential Bus Voltage States

Power Distribution 11 Volts

The slaves obtain power from 50% duty pulses on the bus which are provided by the master. These pulses will vary from 11 volts down to 6, 3 or 0 volts depending on the data level of the dominant bus device.

Figure 4 illustrates the power and data phases. Power is transferred to the slaves during the power phase and data is transferred on the bus during the data phase.

It is possible to impress voltages greater than 11 volts on the bus to activate special programmable memories in the slave devices such as OTP or EEPROM.

It is useful to think of the master creating the levels P and L0. Other devices on the bus, including the master, can pull the bus to a lower state during the data phase with their outputs. These outputs behave like open collector outputs and slaves are Wired-OR together.

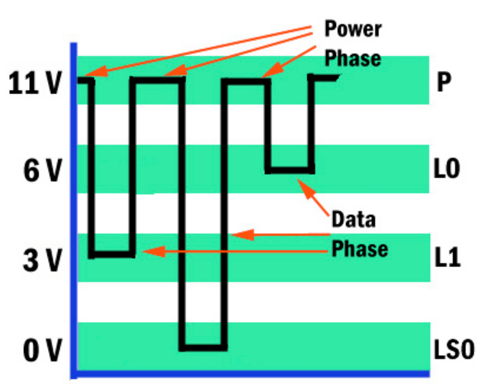

Figure 4 Power and Data Phases on a SbW Bus

L0: Data Level "0" 6 Volts

The data level "0" is represented by a differential voltage of 6 volts and is designated "L0". This level is recessive which means the bus voltage level can be pulled down to data level "1" but not up to P. Only the master can pull the voltage level up to P and then only during the power phase.

L1: Data Level "1" 3 Volts

The data level "1" is represented by a differential voltage of 3 volts. This level is dominant. The master or a slave can pull the level to 3 volts but no device can pull the bus up to 6 volts. Any device impressing a L1 data bit will override any device impressing a L0 bit.

LS0: Special Data Level "0" 0 Volts

The special data level LS0 is represented by a differential voltage of 0 volts. This level is dominant over all other levels in that a device needing to set this level has priority over all other bus devices including the master. It is essential that an airbag deployment have the highest priority level and LS0 allows this.

LS0 is used for the interrupt signal, safing (for deploy messages) and certain error conditions. If a slave detects its data was not properly impressed on the bus, it will take the CRC field down to the LS0 level indicating to the master the data is invalid. LS0 represents the data bit "0" but with a higher priority than L0. L1 still represents the bit "1".

Current Sensing

Some slaves might not be able to fully discharge the bus capacitance at high bus speeds due to their limited drivers. The master will detect the slave data by sensing its current draw on the bus. This will be examined in more detail later.

MESSAGE FRAMES

Messages are sent between the master and the slaves over the bus with predefined message frames constructed by the master. There are two types of frames: D-Frames and S-Frames. D-Frames are used for diagnostic data and deploy messages. S-Frames are used to poll crash sensor inputs at high speeds.

Frames can contain a header, slave addresses, master or slave data and CRC fields. These frames are sent on the bus by the master and the slaves impress their data on the bus at the appropriate time by either doing nothing (L0 = data 0) or pull the bus to L1 (data 1). For LS0, the slave or master will pull the levels to LS0 and L1 as appropriate. The SbW specification calls this impressing of data "modulation". The sending device will verify its data on the bus and will create an error condition if necessary.

D-Frames

D-Frames are used to communicate diagnostic data to and from slaves and for commands to deploy the airbag(s). A D-Frame uses either Point-to-Point or Bitmap addressing. A D-Frame is indicated by the T bit being set to 1. Other bit positions of D-Frames are similar to S-Frames and are described in the next section: S-Frames.

Point-to-Point addressing is used for diagnostic communication to and from the master and the slaves. This mode is able to broadcast commands to the slaves. Figure 5 shows a D-Frame with this addressing mode.

Bitmap addressing is used to control one or more deployable devices at the same time. For example, several airbags can be deployed at the same time with one D-Frame using bitmap addressing. Figure 6 shows a D-Frame using bitmap addressing.

Both addressing methods can be used to send and receive data from the slaves.

The master checks the data it sends out with its receiver to ensure integrity and the E bit is set accordingly. E is set to 1 for an error and to 0 if the data is correct.

Slaves send their data back by modulating the bus current. Due to bus capacitance, especially at high bus speeds, the slaves might not be able to bring the voltage levels down but the master can detect the current modulations.

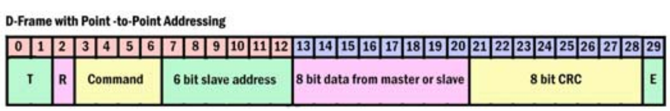

Figure 5 D-Frame with Point-to-Point Addressing

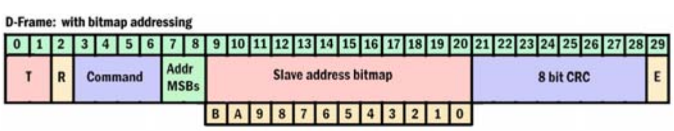

Figure 6 D-Frame with Bitmap Addressing

S-Frames

S-Frames are used to acquire crash data from the input sensors. This is done at the fastest rate of speed possible. The master sends out the S-Frame with the data phases containing L0 in the bit positions where the sensor, which is a slave, will "fill in" the data.

S-Frames are variable length according to the number of slaves on the system and data lengths. Slaves are programmed with the address they will use to determine in which slot of the S-Frame they will impress their data. This also implies to the master the size of the sensor's data length, which can be 4 or 8 bits.

In Figure 7, an example S-Frame is shown. There are three slaves in the system with addresses of 0, 1 and 2 respectively and each is programmed for a data length of 4 bits and system CRC is 3 bits. The frame is made of 25 bits. If this was for a two sensor system, the last 7 bits would not be present. It is possible and common to have longer S-Frames than this example.

The master creates bits 0 through 3 and the slaves fill in the rest. At the conclusion of a frame, the master will enter the bus idle state or initiate a new frame.

The master initiates a frame with the Start-of-Frame and T bit in bits 0 and 1. The T bit (bit 1) will be a "0" or L0 to indicate it is a S-Frame. "R" is a reserved bit and must be at a 0 (L0 or LS0) in order to be recognized by a slave. The SEL bit is used to mix sensors with full and half speeds and is not applicable in this example.

The slave will have been alerted to the presence of this S-Frame by the master putting bits 0 through 2 (SOF) on the bus. The slave with the address 0 programmed into it will impress its data (4 bits in this case) onto the bus.

The slave's receiver circuit will check bit by bit to make sure the data was correctly impressed on the bus. If not, it pulls the bus down to LS0 (0 volts) during its CRC field to alert the master the preceding data is invalid. If the data is good, the CRC field will then be impressed on the bus.

Sensor 1 will then start putting its data and CRC on the bus and so on until all appropriate sensors have responded. Clearly, data is transferred from the slaves to the master quickly without a great deal of overhead.

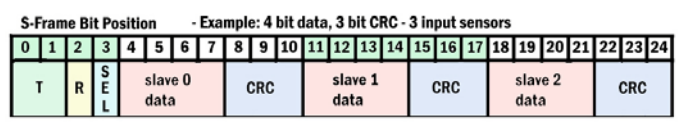

Figure 7 S-Frame with 3 Sensors and 4 bit Data

FRAME BIT FIELDS

Start of Frame and the T bit

Only the master can send message frames. The start of frame (SOF) is designated by the doubling of the power phase period for one cycle followed by one data bit at the normal speed. The value of this data phase bit which is designated the "T" bit, determines what kind of frame is being sent. This two cycle pulse shown in Figure 8 represents the start of a S-Frame. LS0 is not shown for clarity.

T bit = L0: S-Frame

T bit = L1: D-Frame

T bit = LS0: S-Frame that has been initiated by an interrupt during an existing SOF or has been started by the master during a D-Frame.

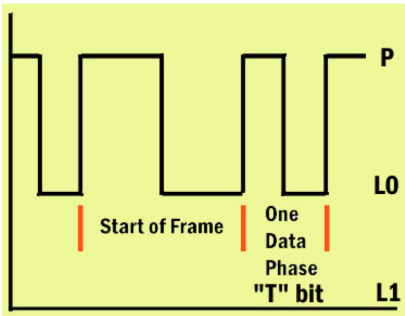

Figure 8 Start of Frame Signal and the T bit

The master initiates a new frame normally after the finish of the preceding one. However, the master can start a new frame at any time. A SOF terminates any frame on the bus and a new frame is started.

R bit: Reserve bit

R is a reserve bit for future expansion. For normal operation, R must be set to a 0 (L0 or LS0). If R is a 1, the slave will ignore this frame. In order to ensure future compatibility, a bus error will not be initiated.

SEL bit

Some sensors are able to update their information at a high enough speed to respond to the master's S-Frames at full speed. Some sensors are only able to update their data at half speed. For example, each high speed sensor can provide fresh data to the master. A sensor updating itself at half speed, would provide two data sets that are the same at the high speed rate of the master. Updating in this context means the slave gets the data from the device, such as a crash sensor, it is connected to. This data then must be passed to the master using a frame the master starts and defines.

It is possible to embed all high updated sensors in the frame and allow the half speed frames to share slots. During the first frame, all the high speed sensors will place their data in their respective slots. One half of the half speed sensors will impress their data on the bus in the slots according to their internal address bit and the state of the SEL bit as provided by the master.

In the next frame, the same high speed sensors will impress their updated data on the bus as before. The second set of half speed sensors will put their data on the bus if the master sets the SEL bit opposite as in the first frame.

The SEL bit could be thought of as an extra address bit for two sensors sharing the same slot in the frame. The sensors sharing the same slot will have the same address and which sensor is allowed to put its data on the bus is determined by the master through its setting of the SEL bit.

CRC field

The CRC field covers all the preceding bits of the frame. A LS0 signal (0 volts) will be impressed on the CRC field to indicate the data is invalid and an error condition is then created.

MESSAGE FORMATS

Messages are divided into two categories: one for deployable devices such as the airbag squib and the input sensors.

Deployment Device Schematic

Figure 9 is a simplified diagram of a typical squib which is a deployable device.

The squib will detonate when the ERC is discharged into it through the HSD and LSD switches. These switches will be solid state devices and not mechanical contacts.

In order for the airbag to be deployed both switches must be closed and the ERC must be charged giving protection against unintentional deployment.

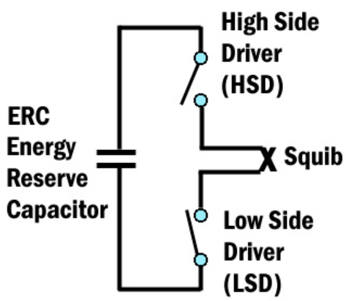

Figure 9 Schematic of a Typical Squib

Deployment Commands

Deploy commands use only D-Frames and ignore S-Frames. The Safing level LS0 (0 volts) must be used in place of the regular "0" L0 in order for the deploy action to be successful.

Commands can be used to deploy the squib or to test it. Testing includes measuring its resistance and leakage current. The four commands possible are listed here.

Command	Definition
00	No deploy: HSD and LSD off
01	Test LSD: LSD on, HSD off
02	Test HSD: LSD off, HSD on
03	Deploy: HSD and LSD on

Sensor Commands

Both D-Frames and S-Frames can be used to send commands and data to slaves and return data. Slaves send back data in S-Frames according to their internal setup and as described in the section describing S-Frames on page 4.

The SbW specification defines how the slaves are addressed and how they accept and return data. Other commands used to manipulate the slaves are device specific and are not covered in this paper.

AIRBAG PLACEMENTS

INTRODUCTION

The initial airbags were installed in the steering column and protected the driver only. Next, an airbag for the passenger was included. This dual airbag system was satisfactory and has saved many lives. But there are some short comings. These include possibility of death to children or small adults and they provide protection only for head on collisions. There is no protection from side crashes and vehicle rollovers.

Front Airbag

Figure 10 shows a standard driver airbag being deployed. Note most of the airbag contact will be applied to the woman's upper body. Her head will contact the upper part of the airbag. If this was a child or small adult, the danger is the main airbag area will contact the head area predominantly and potentially cause serious injury or death as the neck will become dangerously stressed.

Figure 10 Correct Driver Airbag Deployment

Dual Airbags

Figure 11 is a mockup of a dual airbag system. Normally both airbags will deploy in the event of a serious enough crash. The passenger airbag will not deploy if nobody is occupying the passenger seat and the seat is equipped with a pressure switch connected to the initiator, which contains the squib.

In a Safe-by-Wire equipped system, such a switch would be an ideal candidate for a Static sensor. Body positioning detectors using various technologies such as electric fields and multiple switches would also be well served with static sensors because of the low update rates required.

Figure 11 Front Airbags Deployed

Door Airbags

Figures 12 through 15 show several types of door airbags. These are designed to deploy in the event of a side crash. Figures 14 and 15 show airbags providing additional protection for the head and face. Research is continuing to increase safety for vehicle occupants.

Figure 12 Side Airbags

Figure 13 Door Airbag

Figure 14 Window Airbags   Figure 15

<u>Curtain Airbags</u>

Figures 16 and 17 show two types of curtain airbags and are designed to protect the head in a side crash. Figure 16 has a roof section to provide protection in the event of the vehicle rolling over.

Figure 16 Curtain Airbag with Roof Airbag

Figure 17 Curtain Airbag

DEPLOYED AIRBAGS

Figure 18 shows two deployed airbags. Each is a steering column airbag. Note the small round hole in the airbags (most noticeable on the left airbag). This is where the nitrogen gas escapes to rapidly deflate the airbag.

It can be clearly seen how the plastic face of the steering wheel has opened up to allow the airbag to escape. The airbag fabric is usually made of nylon.

The airbag has two wires for the horn if so equipped and two wires for each squib the airbag contains. Some more recent airbags have two squibs for different airbag power levels.

To deploy an airbag manually to disable it for disposal, one needs only supply 9 volts to the squib wires in a controlled area to prevent injuries. With a Safe-by-Wire equipped vehicle, special codes will need to be sent since the squib or the initiator assembly it is in will contain the Safe-by-Wire slave.

Figure 18 Deployed Airbags

OTHER USES FOR SAFE-BY-WIRE

The Safe-by-Wire specification has a narrow application area, namely the operation and maintenance of advanced automotive airbag systems. SbW is not suitable for general network service and will never replace existing networks such as CAN.

There are some interesting areas where SbW could be used. These areas don't usually need the speed of the SbW bus, but could take advantage of the existing semiconductor devices to develop solutions.

<u>Airbag Theft</u>

Not all crashes that cause an airbag to deploy will result in destruction of the vehicle. If the vehicle can be repaired, replacement airbags will be needed. New airbags are expensive and cost around $500 to $600 for standard versions. Advanced multi-level airbags are certain to be more expensive.

Automotive recyclers are providing undeployed airbags for about $200 to $300. Thieves are stealing airbags from vehicles and selling them on the stolen goods market just as they do with car radios. Undeployed airbags are a hot commodity and easily sold.

Since the squib will have a SbW slave chip embedded inside of it, the chip manufacturer could include some security measures that require programming a serial number or other measure to prevent an airbag from being taken from one vehicle and simply installed in another.

Remanufactured deployed airbags must not be used for reliability and safety reasons and perhaps similar security methods can be employed to reduce this problem.

Blasting Caps and Explosives

Manufacturers of automotive squibs are often also in the business of making blasting caps to detonate explosives such as dynamite for construction projects.

Since the tragedy of 9-11, people everywhere are more attuned to the problems of terrorists. A terrorist might purchase or steal blasting caps and dynamite from an area where these materials are fairly easy to obtain such as a mining community or a major construction site. These materials could be transported to a major urban area for a terrorist action where these materials are difficult to get and suspicions very easy to raise.

It could be possible with the SbW equipped squib or blasting cap to program it such that it will only detonate within a certain geographical area as determined by a satellite positioning system (GPS).

Military

The military could benefit from features found in the Safe-by-Wire protocol. The military uses systems designed to protect soldiers and equipment from fast moving threats that give little warning of their approach. These "last-chance" defense systems must activate themselves once they are armed because events can happen too quickly for humans to respond. The Navy's Phalanx system is a good example. Once enabled, any missile approaching the ship will be destroyed automatically by its rapid firing Gatling gun.

There could be some application for systems to activate themselves and provide a defense against fast deploying threats such as grenade launchers and other weapon systems. As the US Armed Forces increase their use of technology, protocols such as SbW will certainly find their way into advanced weapons systems.

CONCLUSION

Clearly a network such as Safe-by-Wire can make a system with enough speed and reliability to fire only those airbags necessary depending on the direction and severity of a crash. This is in addition to several stage airbags and different sizes to save lives of smaller people and even larger people who need more airbag protection. Automatic seat belt tensioners in anticipation of a crash or during the crash can also be handled by Safe-by-Wire. Not all airbags should necessarily be deployed in a crash due to the high cost of airbag replacement and the fact deployed airbags must not be recycled. Not all crashes where airbags are deployed cause the total write-off of the vehicle.

A Safe-by-Wire network can easily deploy dual airbags singly, together or staggered depending on the circumstances of the vehicle and its passengers and the crash severity and direction.

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National Highway Traffic Safety Administration (NHTSA) http://www-nrd.nhtsa.dot.gov/pdf/nrd-30/NCSA/TSF2002/2002occfacts.pdf

Many engineers from various companies are working on Safe-by-Wire. Many contributed information and the author would like to express sincere thanks to them.

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www.dgtech.com/airbags

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APPENDIX

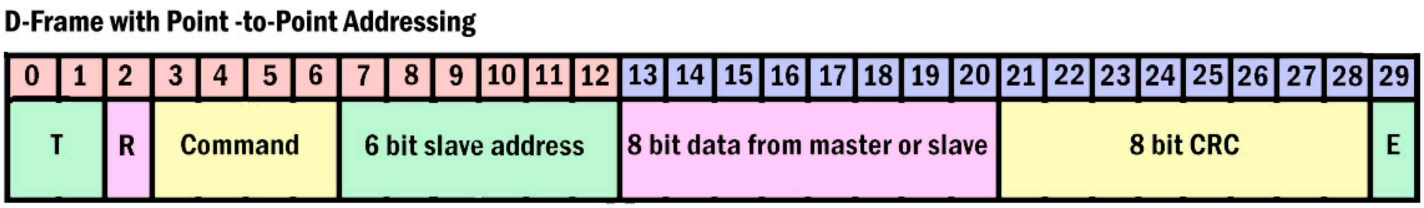

Figure 5 *(copy)* **D-Frame with Point-to-Point Addressing**

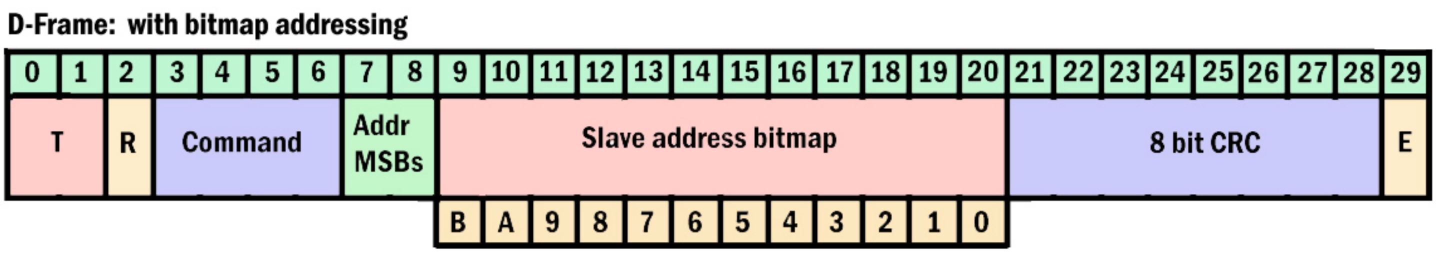

Figure 6 *(copy)* **D-Frame with Bitmap Addressing**

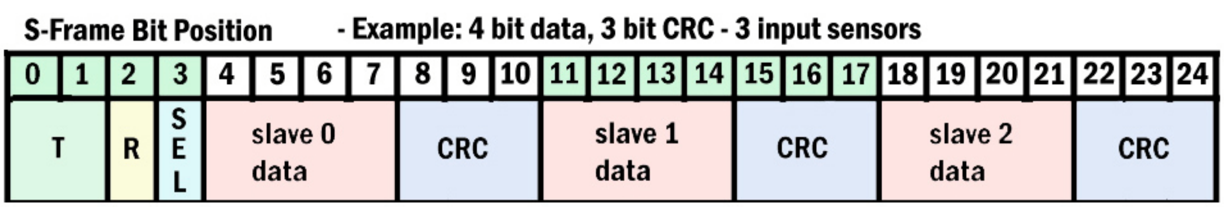

Figure 7 *(copy)* **S-Frame with 3 Sensors and 4 bit Data**