Automated Addressing Failure Detection for Multiplexer Systems

Report NF1676 20230013602

ABSTRACT

Multiplexers are electronic devices which select between several input signals and deliver an output signal. Also known as data selectors or mux, multiplexers are commonly used in circuit design to provide signal switching, simplify hardware and manufacturing, and decrease cost. Systems which use a digital mux as a switch or selector are vulnerable to events called addressing failures, arising in hardware or software. An addressing failure results in the system requesting, or the mux delivering, a data signal other than the one intended. The unintended use of this erroneous signal may lead to system-level failures. This paper discusses a novel method of automatic detection for addressing failures, utilizing multiplexer channelization and a monitoring algorithm.

Gwyer Q. Sinclair
National Aeronautics and Space Administration
Marshall Space Flight Center

Automated Addressing Failure Detection for Multiplexer Systems

Gwyer Q. Sinclair, National Aeronautics and Space Administration

Key Words: Channelization, Circuit Design for Reliability, Failure Detection, Multiplexer

ABSTRACT

Multiplexers are electronic devices which select between several input signals and deliver an output signal. Also known as data selectors or mux, multiplexers are commonly used in circuit design to provide signal switching, simplify hardware and manufacturing, and decrease cost. Systems which use a digital mux as a switch or selector are vulnerable to events called addressing failures, arising in hardware or software. An addressing failure results in the system requesting, or the mux delivering, a data signal other than the one intended. The unintended use of this erroneous signal may lead to system-level failures. This paper discusses a novel method of automatic detection for addressing failures, utilizing multiplexer channelization and a monitoring algorithm.

1 *INTRODUCTION*

Addressing failures arise in digital mux systems, which switch between inputs via data selection lines. Systems which encode multiple data streams for simultaneous transmission (like frequency or wavelength division multiplexing [1]) are not susceptible to addressing failures. When using a digital mux, reliability can be improved by utilizing automatic detection of addressing failures. Automatic detection of failures allows, in many cases, for automatic corrective action. In other cases, it provides a diagnostic which can increase system availability.

1.1 *Digital Multiplexer Mechanics*

A mux selects between input signals, forwarding one selected output. A mux of 2^n inputs has n select lines ($S_1, S_2, \ldots S_n$) which utilize binary logic gates to select the desired input for forwarding [2].

1.2 *Channelization*

Channelization refers to the combination of signals to share one transmission medium. In a digital multiplexing scheme, channelization is the order by which the signals are connected to the mux inputs. This connection is a physical arrangement.

Table 1 – 4-to-1 MUX Channelization

Channelization (Ex. Signals)	Channel (Decimal)	S_2 (Binary)	S_1 (Binary)
Signal A	0	0	0
Signal B	1	0	1
5 V Reference	2	1	0
0 V Ground	3	1	1

1.3 *Addressing Failure Mechanics*

An *Addressing Failure* (AF) is any one of a family of related failures, initiated by causes in hardware or software. An AF is identified based on its effect on the mux system; it is any failure which causes an unintended signal to be selected by the mux. The following are examples of events leading to AF [3]:

- Short or open circuit affecting one or more select lines
- Defect in logic gate, component, or integrated chip
- Random bit flip in electronic memory
- Memory leak or buffer error in software
- Logic error in software

AFs which act upon the select lines of a mux can be characterized as ‘stuck’ binary digits; a select line which is nominally commanded to either 0 or 1 is limited to a single value. This effect can be instantaneous, persistent, or permanent. Referring to Tables 1 (nominal state) and 2 (failure state), consider a failure causing S_2 to be stuck high. Channels 2 and 3 will telemeter in response to a request for or an attempt to transmit channels 0 and 1, respectively. Channels 0 and 1 will be unreachable signals.

Table 2 – 4-to-1 MUX Channelization (Addressing Failure)

Channelization (Ex. Signals)	Channel (Decimal)	‘Stuck’ S_2 (Binary)	S_1 (Binary)
5 V Reference	(2)	(1)	0
0 V Ground	(3)	(1)	1
5 V Reference	2	1	0
0 V Ground	3	1	1

AFs in software often manifest as ‘requesting’ the wrong channel rather than ‘receiving’ the wrong one. In such a case, no failure in the hardware has occurred, and action may allow for the failure to be corrected automatically. The system level effect of each type of AF (either request or receipt of the wrong channel) are the same; a channel other than the intended is utilized by the system.

The potential exists for multiple addressing failures to occur simultaneously, or for a single failure to affect multiple select lines. As the case of a single bit failure is most common, compounded failures are not discussed further.

2 *DESCRIPTION OF METHOD*

The detection method requires channelizing the mux such that an AF always causes a telemetered value which is differentiable from the expected value. Paired with a monitoring function [4], the system may then identify when an AF has occurred. Depending on the specifics of each design, the system may then react to the failure as the designer intends.

2.1 *Identify Expected Value Range*

Central to the ability to differentiate signals is understanding the *Expected Value Range* (EVR) of each signal. Some are straightforward; the EVR of a ground (GND) is a constant 0V, that of a 5V supply a constant 5V. Variable signals transmitted to a mux input may have many ranges, whether they are measured directly in voltage or current (analog signal) or constructed in software from binary inputs (digital signal).

A typical analog signal may be exemplified by a piezoelectric sensor which outputs a voltage differential in response to physical pressure, force, or vibration [5]. Under normal atmospheric pressure (the lowest it will nominally sense), the sensor may experience 29 – 31 inHg and generate a voltage differential of 0.5 mV in response. Subjected to a pressure change up to the system's maximum operational pressure, the sensor's output may increase to 2.5 mV. An analog signal's EVR is the expected range of values that will be produced under nominal operating conditions in the system. The EVR of the pressure sensor would be 0.5 to 2.5 mV, with the conversion to an amount of inHg happening in software.

Digital signals are harder to differentiate, as the binary "0 or 1" has less variability than an analog value. A digital version of the pressure sensor may generate an 8-bit string 00011110, which can be interpreted by software to mean "30 inHg" if it is known that the signal is being received from a pressure sensor and should have the units "inHg" [6]. The digital pressure sensor may have an EVR from "00011110" to "01011100" (understood by software as 30 to 92 inHg). Note the standard practice is for many digital signals to include error detecting or correcting codes that are transmitted alongside or appended to their data. These are discussed further in section 3.1.

2.2 *Importance of Expected Value Range*

Receiving a signal outside of the EVR generally indicates an error or failure in the system. For example, if the pressure sensor returns 0 mV while under atmospheric pressure, it can be determined that either the sensor's environment has become a vacuum, or there is an open circuit or other error in the system. Similarly, receiving a voltage differential higher than the EVR's maximum may indicate either an actual pressure over the system's maximum design pressure, or some short or other failure in the system. Failures of these kind are detectable by comparing a received signal to its EVR, which can be done without any special attention paid to the channelization of signals [4]. However, channelizing based on EVR can add detection for AF that was previously impossible.

Consider a system utilizing two sensors X and Y attached to MUX input signals; they may be the same kind of sensor or different, so long as they transmit with the same EVR. In the event of an addressing failure causing X to be telemetered in the place of Y, the system would be unable to detect the failure because the received signal X is still within the EVR of Y. The system would erroneously use the measurement from X in the place of Y, perhaps resulting in further failure(s).

2.3 *Construct Sets of Signals by EVR Similarity*

For the set A of all input signals to the mux, construct subsets A_1, A_2,… such that each signal is in at least one subset, and the union of all subsets is equal to A. Order A arbitrarily (perhaps creating an ordered list by current channel for existing systems, alphabetically, or any other listing). Sequentially for each signal in A, determine its EVR and if any existing subsets contain signals with overlap in EVR. If any such subset exists, place the signal into it. If no such subset exists, create a new one and place that signal into it (the first signal in A will be in a new subset A_1, the EVR of which will be compared to the second signal and so on). It is important to note that there are always enough signals to fill every mux input; any un-assigned signals are an empty signal, with an EVR of constant 0V.

After this has been completed for each signal in A, there will be one or more subsets, each of which contains signals with overlapping or identical EVRs. In the event of an AF, it is preferable for a signal in A_n to failover into any signal which is not also in A_n. In this way, no single AF can cause telemetry of a signal that can be mistaken as any other signal in the same subset. Any system with signals has a minimum of one such subset A_1 (if all signals have overlapping or identical EVR), and a maximum number of subsets $A_1, A_2, \dots A_n$ where n is the number of signals in A (if all signals have mutually differentiable EVR).

2.4 *Channelize the Multiplexer*

After grouping a mux system's signals into subsets by EVR, the designer may then identify a channelization of the mux to accommodate those signals in channels that cannot failover to the same subset in the event of a single AF. Recall that channelization on a digital multiplexer refers to the order in which signals are physically connected to the mux inputs. The output channel is determined via logic gates implementing binary signals delivered via multiple 'select' lines. A mux of 2^n inputs has n select lines (S_1, $S_2, \dots S_n$), which create a binary expression corresponding to the channel number in decimal.

Individual AFs can be generalized as causing a single 'stuck bit' in the binary expression $S_nS_{n-1}\dots S_1$ which corresponds to a selected mux input channel. Mathematician Richard Hamming described binary expressions differing by one bit as having *Hamming Distance 1* [7].

Table 3 – Hamming Distance

Expression A			Expression B			Hamming Distance
S3	S2	S1	S3	S2	S1	
1	0	0	1	0	0	0
1	0	0	1	0	*1*	1
1	0	0	*0*	*1*	0	2
1	0	0	*0*	*1*	*1*	3

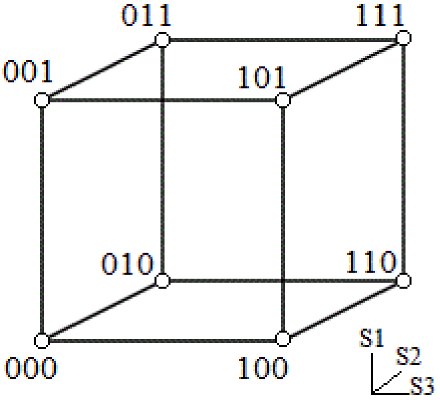

Figure 1. A Hamming Graph (8-to-1 mux)

The relationship between the single ‘stuck bit’ caused by an AF and the Hamming-Adjacency of mux channels is illustrated in constructs called *Hamming Graphs* [8]. Figure 1 illustrates a Hamming Graph representing an 8-to-1 mux. The figure is a unit cube in cartesian space, with the axes corresponding to select lines S3, S2, S1. Each vertex on the cube can conceptually correspond to a mux input channel, and those vertices connected by an edge have Hamming Distance 1. Any AF manifesting a single bit flip will cause the system to telemeter a channel with Hamming Distance 1 from the intended channel. In the representation of the Hamming Graphs, designers may visualize the effect of an AF as failing to a state adjacent (connect by an edge) to the one originally intended.

Consider an AF causing select bit S_3 to be ‘stuck high’ as causing a translation from the left-hand plane ($S_3 = 0$) to the right ($S_3 = 1$), resulting in selecting 100 instead of 000, 101 for 001, & so on.

With the Hamming Graph established as a representation of the mux channelization, refer to the subsets constructed in the previous section. A 2^n-to-1 mux must have a maximum subset size of 2^{n-1} for optimal channelization to be possible. In other words, if more than half of the signals in *A* have the same EVR, one cannot guarantee that an AF always causes a failover into a channel with a different EVR. Section 3.2 develops some potential solutions if this problem arises.

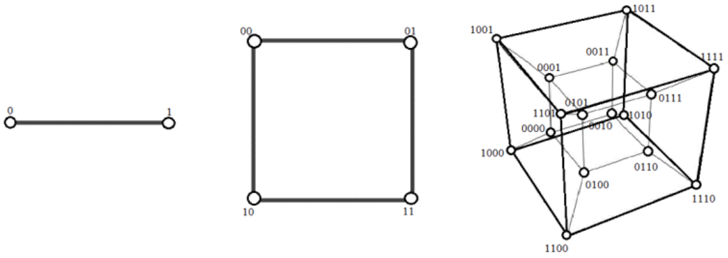

Figure 1. Hamming Graph Representations of 2, 4, and 16-to-1 MUX

If all subsets of *A* are at or below the maximum size allowing for optimal channelization, assign signals to nodes of the Hamming Graph (representing channels) such that adjacent nodes contain no members of the same subset of *A*. This paper adapts a common application of graph theory, the “Vertex coloring” or “K-coloring” problem, to achieve this [9].

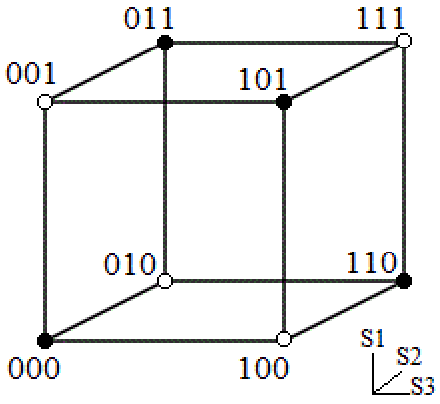

Figure 2. K-Coloring of the Graph (K=2)

Figure 2 is a K-coloring of Figure 1 with K=2. There are two colors (dark and light). Any node colored dark (000, 011, 101, 110) experiencing an AF on a single select line will only telemeter a channel colored light, and vice versa. The K=2 coloring demonstrates that as few as two subsets of the maximum size (each containing half of the signals connected to a mux) may be optimally channelized. A K-coloring may be completed with a K as large as the number of nodes, if each is assigned a unique color. Channelizing in such a way will cause an addressing failure to telemeter a detectably incorrect value (one outside the intended signal’s EVR).

2.5 *Implement Monitoring Function*

The monitoring function which pairs with optimal channelization will differ for each system. Generally, it will take the form of a software function which observes the inputs and outputs of the mux system and compares them to the known Expected Value Range (EVR) for the intended signal [4]. If the received signal is outside the EVR, a failure is reported. This event may mean:

- An addressing failure (AF) has occurred, and the received signal is not the intended
- The address is correct, and the signal or system has failed in another way, potentially in the monitoring function itself

The use of monitoring functions for failure detection is already widespread in software programs, and the use of EVR as a monitoring parameter can already detect some types of failures. It is the optimal channelization of mux inputs that allows AFs to be added to the list of failures that can be automatically detected via EVR-to-output comparison.

2.6 *Example*

In an industrial safety application, an 8-to-1 multiplexer is utilized in a monitoring and control loop for a pressurized gas vessel. The system has a 5V voltage reference, two temperature sensors, and two pressure sensors. Consider all four sensors to have the same EVR of 10-15V; even though they measure different phenomena, they all transmit their data in Volts and under nominal conditions are expected to transmit in the same range. Table 4 describes a non-optimal channelization scheme.

Table 4 – Non-Failure Example in a Pressure Vessel

Channel	Signal	S_3	S_2	S_1
0	Pressure Sensor 1	0	0	0
1	Pressure Sensor 2	0	0	1
2	5V Voltage Reference	0	1	0
3	Temperature Sensor 1	0	1	1
4	Temperature Sensor 2	1	0	0
5	Unassigned Channel 1	1	0	1
6	Unassigned Channel 2	1	1	0
7	Unassigned Channel 3	1	1	1

Consider an AF caused by a short of the leading select bit S_3 to the 5V reference, causing S_3 to be stuck high (always 1). The system, expecting the signal from channel 0, receives values from channel 4 instead. With the wrong information utilized in a calculation of the vessel's internal pressure, the system automatically adjusts to compensate. This correction to a non-existent issue becomes a real failure, as the vessel is driven to an out-of-tolerance condition.

Applying the method from Section 2, signal subsets of indifferentiable EVRs are constructed. First, a subset A_1 containing Pressure Sensor 1 is created. The other sensors have the same EVR and are also placed in A_1. The 5V reference has a different EVR than all the signals in A_1 and is placed in a new subset A_2. The unassigned channels with EVR = 0V are placed in a new subset A_3. Now a K=3 coloring of the graph may be completed to visualize a new channelization (Figure 4).

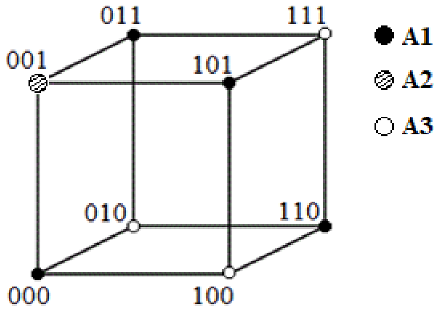

Figure 2 - K=3 Coloring of the Graph

Table 5 – Updated Channelization for the Pressure Vessel

Ch.	Signal	S_3	S_2	S_1	EVR (V)
0	Pressure Sensor 1	0	0	0	10-15
1	5V Reference	0	0	1	5
2	Unassigned Channel	0	1	0	0
3	Pressure Sensor 2	0	1	1	10-15
4	Unassigned Channel	1	0	0	0
5	Temperature Sensor 1	1	0	1	10-15
6	Temperature Sensor 2	1	1	0	10-15
7	Unassigned Channel	1	1	1	0

By following the channelization in Table 5, an AF experienced on any channel cannot cause an unintended signal with the same EVR to be erroneously selected. Thus, a monitoring function can identify a failure by comparing received signal to EVR. Once detection is achieved, the system may respond by initiating safe automatic shutdown.

3 *IMPLICATIONS FOR A MUX SYSTEM*

3.1 *Comparison to Other Failure Detection Methods*

As discussed in Section 2.5, Expected Value Range (EVR) as a monitoring parameter can be used to detect some failures regardless of how the multiplexer (mux) is channelized [4]. By optimally channelizing the mux, however, addressing failures (AF) become detectable and in some cases, differentiable from other types of failures.

In digital communication, the reliability of data transmission is sometimes protected via a code, check, or parity sequence appended to the desired information. Parity check, Hamming Code, or other error-detecting codes can identify transmission errors and noise in a single stream of data, and could be utilized alongside a technique like this one [7]. Error-detecting codes such as these are not, however, replacements for the method described in section 2. In the case of an AF, the data being sent is not corrupted by noise or itself in error; it is the system's interpretation of what that data means that introduces the error. As such, consider error detection and correction codes as solving a separate problem from the method defined in this paper.

The concept of prefixing the transmitted data by a more descriptive code, capable of uniquely identifying the source of the signal, is utilized in Code-Division Multiplexing (CDM) [10]. In CDM, a signal is assigned a sequence of bits which allows it to be distinguished from others by the receiver. The use of a distinguishing code may be utilized by the designer of a digital mux system, if the potential drawbacks are considered:

- The function which appends the code to the signal may itself be susceptible to addressing failure
- Including a distinguishing code means a larger share of the transmission media is unavailable to transfer of the actual desired data (overhead cost)
- The added distinguishing code is itself susceptible to failures (system availability)

In applications where CDM is in use (especially in multiple-access networks), physical channelization on one mux is rare.

3.2 *When Optimal Channelization is Impossible*

In the event that the EVRs of a system's signals are too similar to support full automatic detection, a designer may maximize detection by placing as many signals as possible into ideal channels. It is also possible to modify a signal's EVR, for example by introducing gain to an analog signal, or a code to a digital one, in order to create differentiable EVRs for detection. This technique would, however, require more overhead to add the distinguishing feature and potentially remove it after demultiplexing, and has the potential to introduce noise or other failure to the system. Designers also have the option of using a larger mux than necessary for their inputs, so that they have empty channels (EVR = 0V) with which to channelize. However, increasing hardware complexity also comes with an inherent reliability cost – whether or not that reliability loss is worth the gain of implementing AF detection, depends on the individual system.

3.3 *Estimated Impact on System Reliability*

Reliability analysis for sensor-interfacing avionics devices in a spaceflight application is utilized to estimate the impact of detecting and correcting AF on system reliability. The applicability of this example to every other multiplexing system should be understood to vary. In addition, the analysis is proprietary, and details cannot be shared publicly, so its veracity cannot be proven to the larger reliability community. For these reasons the estimated impacts are presented as notional only and it is recommended that reliability engineers and electronics designers determine the merit of this method for their own applications as appropriate.

The reliability analysis utilized four data sources:

- Piece Part Reliability Calculation [11]
- Failure databases such as NPRD [12]
- Vendor supplied data from testing
- Vendor supplied data from historical field operations

Data from these sources was processed via various methods to compute expected reliability, including Parts Count Method utilizing Series / Parallel / K-of-N configurations as appropriate, and Parts Stress Prediction Method. In the avionics devices under analysis, it was determined that AF were not among the most common failure modes, but their likelihood was not so low as to be non-credible or not assessed. These failure modes contributed noticeably to the reliability of a human-spaceflight program and could result in catastrophic (loss of mission and life) effects.

Utilizing the same methods and input data but removing all addressing failures from the analysis (to simulate the introduction of 100% detection and correction of AF into the system) mission reliability increased by approximately .1%. In addition to the reliability increase, the application of this technique removes critical failures from the system.

The applicability of this example is strongest to other space launch or aircraft systems. Systems which rely differently on their sensing data, have more or fewer critical failure modes or signals, or are used in different environments will have highly different outcomes. It is certain that any system which is susceptible to AF, will have a reliability increase when the deleterious effects of AF are removed.

Any reliability increase is valuable to systems with very exacting requirements, especially systems with a human safety impact. Increases are compounded in effect when the system has either a very long runtime or a very high population benefitting. Additionally, the financial impact of increased reliability, and therefore availability, can be highly valuable.

3.4 *Estimated Impact on System Cost*

The burden of the cost for implementing this failure detection method is borne in the development a new or modified monitoring function. There is no hardware cost to channelize a multiplexer via the principals described in section 2, as opposed to some other channelization method. The only overhead cost experienced is that of the system resources required for the operation of the monitoring function.

4 SUMMARY

Multiplexers and their signals are ubiquitous. The amount of data being sent over multiplexed lines is higher than ever. These devices are susceptible to a family of failures which is generally undetectable, called addressing failures, which arise in hardware or software.

Section 2 describes a new method at a designer's disposal when architecting a system for maximum available reliability. Designers are advised to consider the low cost for implementing this method when deciding which methods to utilize in maximizing their system's reliability.

Expected Value Range (EVR) of a system's signals is an essential component to the effectiveness of channelization on AF failure detection. If all signals have a different EVR, channelization is not necessary; implementation of an EVR check into a monitoring function is sufficient to identify addressing failures. If all a mux's signals have the same EVR, automated AF detection via channelization is not possible without some hardware changes. Other techniques may modify or be used in addition to this method.

REFERENCES

1. S.M. Basir, G.A. Mhdiraji, A. Malekmohammadi, N.H. Ibrahim, A.F. Abas and M.K. Abdullah, "Demonstration of Duty Cycle Division Multiplexing with bit error rate estimation," in 2009 IEEE 9th Malaysia International Conference on Communications (MICC), 2009.
2. A. J. Diefenderfer, Principles of Electronic Instrumentation. PA: Saunders College Publishing, 1972.
3. "TMUX1308_data_sheet" *www.ti.com*. https://www.ti.com/product/TMUX1308#support-training.
4. P. Hazy &. R. Seviora, "Automatic Detection of Local and Global Software Failures," in 2005 Siberian Conference on Control and Communications, 2005, pp. 32–37.
5. E. Dertien, P. Regtien, Sensors for Mechatronics. Elsevier, 2018.
6. B. C. Patel, G. R. Sinha, N. Goel, Introduction to Sensors. ResearchGate, 2020.
7. R. W. Hamming, "Error Detecting and Error Correcting Codes," Bell sys, no. 29, pp. 147–160, 1950.
8. A. E. Brouwer & W. H. Haemers, Spectra of Graphs. New York, NY: Springer, 2012.
9. R. Diestel, Graph Theory. Berlin, Germany: Springer, 2017.
10. K. K. Ho, "Architectural Design of a Code Division Multiple Access Cellular System," in Vehicular Technology Society 42nd VTS Conference - Frontiers of Technology, 1992, pp. 47–50.
11. U.S. Department of Defense, "MIL-HDBK-217 Reliability Prediction of Electronic Equipment," 1995.
12. "Nonelectronic Parts Reliability Data Publication (NPRD-2016)," *Quanterion Solutions Incorporated*. https://www.quanterion.com/product/publications/nonelectronic-parts-reliability-data-publication-nprd-2016

BIOGRAPHY

Gwyer Q. Sinclair
Safety and Mission Assurance, NASA MSFC
4200 Rideout Rd SW
Huntsville, Alabama 35808 USA

e-mail: gwyer.q.sinclair@nasa.gov

Gwyer Sinclair serves as a Reliability Engineer for NASA space flight programs, and previously held similar positions in private industry. Originally from Green Bay, Wisconsin, Gwyer earned a bachelor’s degree with honors in electrical engineering from the University of Alabama in Huntsville in 2018. Gwyer is a member of the Huntsville Society of Reliability Engineers and has presented several times at their Huntsville RAMS training summit.