PHYSICAL LAYER FAULT TOLERANCE FOR FOUNDATION FIELDBUS NETWORK

A Thesis

Presented to

the Faculty of the Department of Electrical and Computer Engineering

University of Houston

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

in Computer and Systems Engineering

by

Mohd J. Alam

December 2014

PHYSICAL LAYER FAULT TOLERANCE FOR FOUNDATION

FIELDBUS NETWORK

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Abstract

The open all-digital communications protocol Foundation Fieldbus offers a wide range of benefits to process control systems through data reliability, diagnostics, interoperability, and distribution of controls to an unprecedented level. However, lack of media redundancy on its H1 networks can compromise the availability of view and control of a critical process. In this thesis a novel approach is proposed to add fault tolerance by achieving media redundancy on H1 networks. It presents an H1 topology framework capable of detecting and handling a break in the network to allow control and communication to continue uninterrupted. A test network with a functional prototype was constructed to evaluate real-world control application in fully redundant settings. Results showed that continuity of control and supervisory view to the process remained uninterrupted when a cable break is induced, resulting in a fault tolerant H1 network.

Table of Contents

List of Figures

List of Tables

1. Introduction

Foundation Fieldbus (FF) interconnects intelligent instrument systems and controllers in two hierarchical networks to enhance overall data reliability and diagnostics capacity of the control system while distributing the control elements further into intelligent instruments across the plant floor. Fieldbus H1 as illustrated in Figure 1.1 is one of these two hierarchical networks (also referred as H1 segments) that interconnect sensors, actuators, and I/O at the plant-floor level. By pushing controls into instruments at H1 networks Fieldbus enables further distribution of control; however, the H1 specification offering no physical layer (media) redundancy raises serious reliability concerns for the security and communication of such system. It is especially acute for critical process control applications where loss of view or control could be catastrophic. Engineers have been addressing this issue by doubling up various components of the H1 network (power conditioners) and access to the network (Linking Devices) from the supervisory networks.

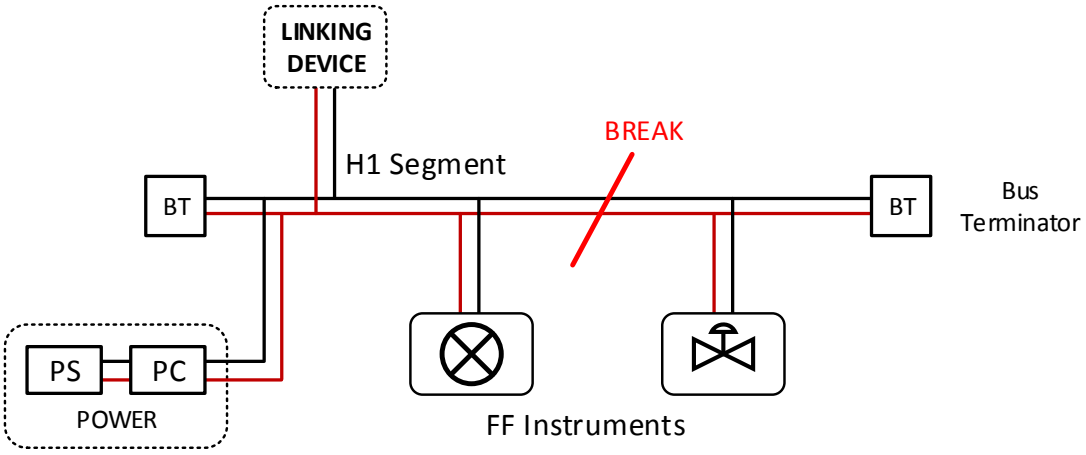


Figure 1.1 Fieldbus H1 Segment.

As a result, Foundation Fieldbus systems often get deployed as a digital I/O network for proprietary controllers without taking advantage of its control distribution capabilities. System designers often mitigate this limitation and reduce risks by limiting the number of instruments

allowed on a segment as well as assigning the instruments with similar criticality (from process point of view) on the same segment. Even with all these actions, at the end of the day, the H1 segment still hangs on a single shielded twisted pair of cable, and a break in the segment causes partial or complete loss of view and control. The goal of this thesis is to develop a topology framework for H1 networks capable of withstanding a trunk-level cable break and maintain uninterrupted control and communication on the segment with a much desired Fault-Tolerant H1 network.

Control in the Field (also referred as CiF) is a key enabler of Foundation Fieldbus technology to achieve a more available system by achieving Single Loop Integrity through further distribution of control from a centralized controller to smart field instruments. CiF offers enhanced process integrity with deterministic communication reliability and a faster read-execute-write cycle performance. CiF provides superior reaction to disturbances in the process making it perfectly suited for faster processes [1]. Figure 2 illustrates this form of distribution of control. Benefits offered by CiF may easily be compromised by a break in H1 segment medium. The focus of this thesis is to ensure these CiF applications run uninterrupted even when a physical break occurs on the H1 segment trunk.

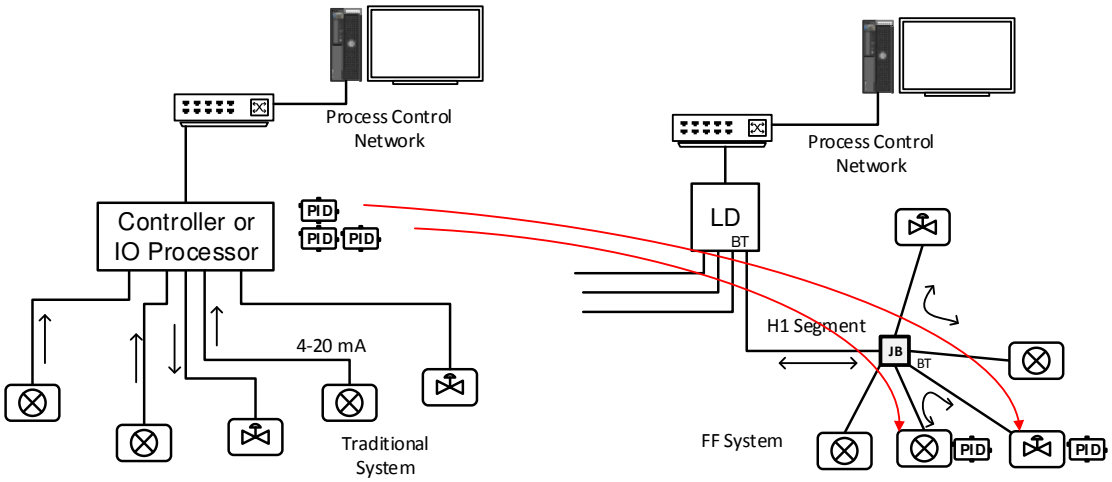


Figure 1.2 Control in Field (CiF) by FF.

Simply by doubling up the network cable would not necessarily provide media redundancy for H1 networks. IEC61158 [2] specifies how the H1 physical layer network must be implemented, and there are limitations in terms of maximum length, number of instruments per segment, and number of bus terminators. Consideration must be taken so that by making the segment redundant does not take away the overall segment length available for an application. H1 segments must also have exactly two bus terminators (BT) at any given time, and breaking the trunk (segment) certainly would put them out of balance, so new terminators must be activated and deactivated automatically at fault to maintain exactly two terminators per segment. Proposed framework considered both of these aspects of the FF segment design while keeping uninterrupted *control* and *communication* as its critical focus.

The rest of the thesis is organized as follows. Chapter 2 provides a brief introduction to the Foundation Fieldbus technology and further analysis of its challenges mitigated in this thesis. It is important for one to understand the H1 protocol and how these networks are constructed in order to identify their vulnerabilities and strengths; therefore, appreciate the solution proposed in this thesis. Chapter 3 is organized to review general fault tolerance in Foundation Fieldbus and some works by others in the industry to mitigate similar concerns. This chapter also outlines the solution framework and components proposed in this thesis for physical layer fault tolerance of the H1 network.

The prototype of a functionally equivalent apparatus is detailed in Chapter 4, where it is used with a redundant test segment to evaluate its performance during an induced segment break. The data-captures and their analysis are also documented in this chapter to provide evidence to its capacity of fault tolerant operation and the efficacy of the solution proposed in this thesis. Chapter 5 concludes the thesis.

2. Background

2.1 Foundation Fieldbus H1

The Foundation Fieldbus is an open industrial network protocol for intelligent instruments and controllers in process automation systems enabling real-time distributed control. It emerged during the late nineties out of a necessity to improve control system reliability with increased data reliability, enhanced diagnostics, distributed control, interoperability, single-loop integrity, and cost reduction. Driven by the end-user needs, process-control and manufacturing automation vendors formed the not-for-profit organization Fieldbus Foundation [3] to develop this open, international, and interoperable bus technology. The H1 and HSE – two standards are offered by the Foundation Fieldbus to implement a hierarchical network of instruments & sensors, controllers, I/O (Input Output) Processors, operator stations, and other subsystems that comprises modern supervisory control systems. Figure 2.1 shows a high level representation of the plant network hierarchy. The H1 (31.25 Kbit/s) network interconnects field equipment such as sensors, actuators, and I/O at plant-floor level, while the HSE (100 Mbit/s) or High Speed Ethernet provides integration of high speed controllers, H1 subsystems, Data Servers, and

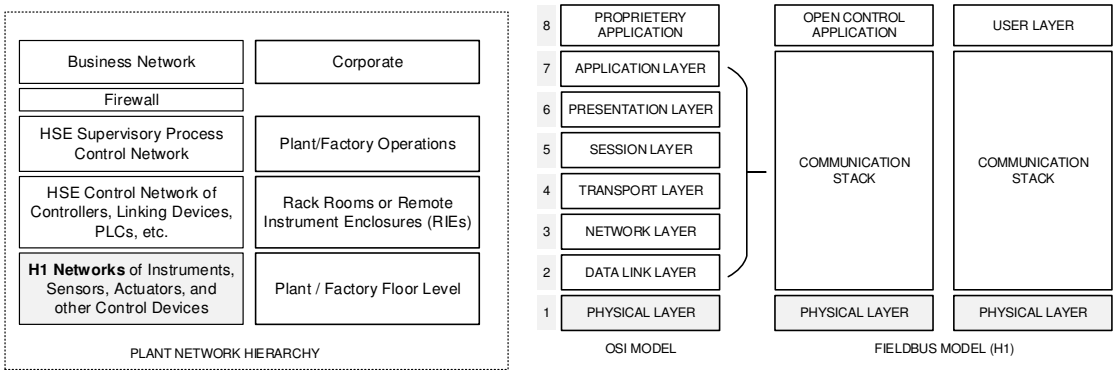


Figure 2.1 Plant Network Hierarchy and Fieldbus Model.

Workstations. The FF technology adopted the Open Systems Interconnect (OSI) layered communication model to develop its own layers of communication models. The Fieldbus model

primarily consists of a Physical Layer, the Communication Stack, and the User Application Layer. The OSI layers 3 to 6 are not used by the Fieldbus model, and it is specified to be Open in order to ensure interoperability between the FF instruments from different vendors. The Data Link Layer of the Fieldbus model resides in the Communication Stack. It supports deterministic communication relationships with a publisher/subscriber mechanism, while the asynchronous data exchanged using a client/server relationship. The Foundation Fieldbus uses token passing mechanism to establish communication. The Device holding the token can publish data on the network, and then pass the token back to an entity called the Link Active Scheduler or LAS. Definition of the LAS and its roles are to follow in the next few sections.

H1 Segments

The FF Physical Layer defines the H1 as a network of measurement instruments, sensors, actuators, and other I/O devices on a multi-drop shielded twisted pair cable. This network resides at the lowest level of the process control network hierarchy at the plant-floor near the process areas. It operates a 31.25 kbit/s half-duplex two-way communication system. The H1 segments

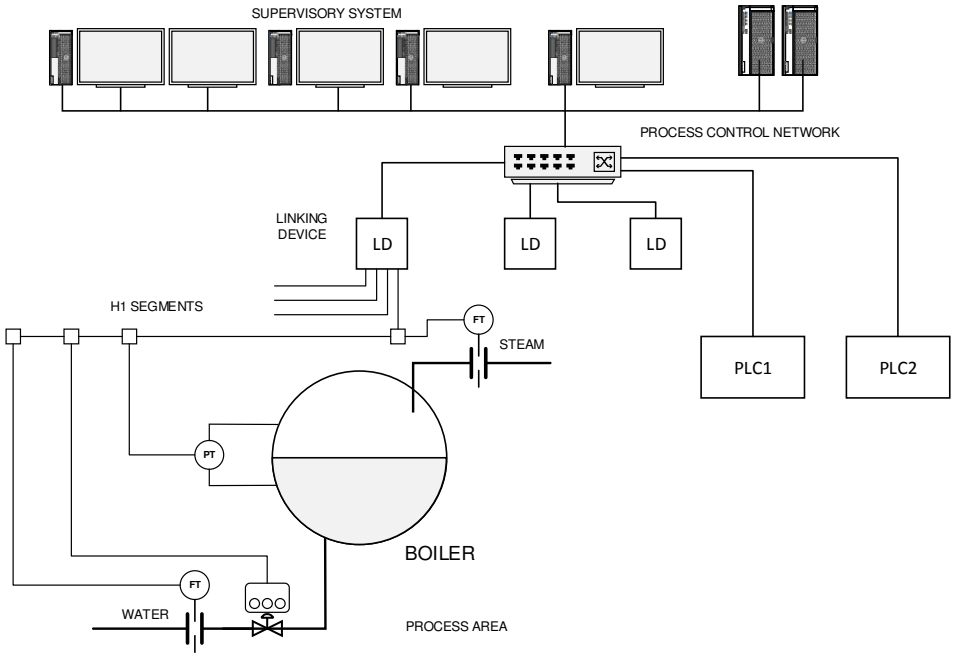


Figure 2.2 Fieldbus Control System (H1 Segment) Overview.

are collected into Bridges or Linking Devices (LD) which integrate them into the upper level Process Control Network (PCN). The Bridge or Linking Devices are also sometimes referred as Fieldbus Interface modules, and they could either support the Foundation HSE or other proprietary protocol to transfer measurements and control data between the process area and the supervisory system. Figure 2.2 shows an overview of an H1 segment and its integration into the overall process control system.

Data Link Layer – Messaging

The H1 Physical Layer is defined by IEC 61158 @31.25 Kbit/s. The Power to the instruments and the communication messages are delivered using the same pair of shielded twisted pair cable. The communication signal is encoded using the Manchester Biphase-L technique. A voltage Mode signaling is used to create 1.0v peak-to-peak modulated voltage on top of the DC supply voltage. A positive transition in the middle of a bit time is interpreted as a logical "0" and a negative transition is interpreted as a logical "1". Figure 2.3 shows the Clock, FF Data, and the Manchester encoded FF signal.

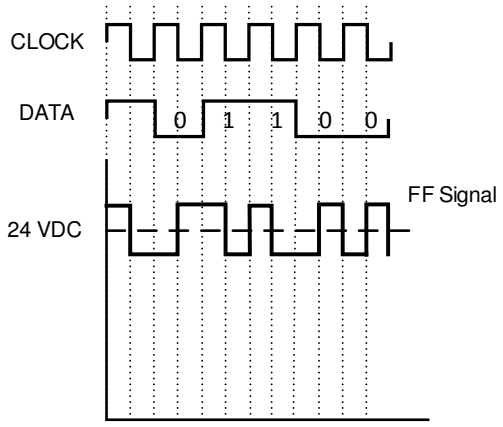


Figure 2.3 FF Signal and Data on Same Wire.

Network Topologies

The H1 segments are typically constructed using a dc power supply (PS), a power conditioner (PC), two bus terminators (BT), one or more junction boxes (device couplers) to connect devices, and shielded twisted-pair cable. The instruments are connected in multi-drop

fashion in parallel at the device couplers. The device couplers come in varying functionalities. They are passive components with features that enable adding and removing instruments to and from the segment safely. The theoretical limit on the number of instruments attached to a H1 segment is 16 or 32 depending on whether or not the devices draw power from the segment. Figure 2.4 shows a simplified representation of an H1 segment completed with a Linking Device. The junction boxes, shielding, and grounding of the segment were omitted from this figure for clarity. The number of devices in a segment is primarily limited by the power and impedance

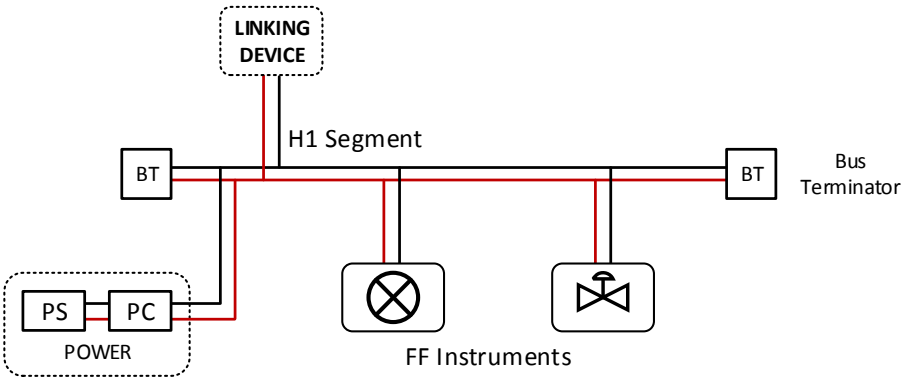


Figure 2.4 Fieldbus H1 Segment.

characteristics of the segment cable and its length; however, the realistic number is fewer than 16, since the control and cycle time must also be considered along with the cable resistance and signal attenuation. The design of the H1 segment loading is beyond the scope of this thesis, but to simplify the concept, it can be said that, a longer segment and/or a faster cycle time reduces the number of devices in a segment. The H1 segment can be up to 1.9 km when the main trunk and all of its spurs are added up. Since H1 is a parallel multidrop network, it could be arrange in a number of ways. The frequently used topologies include Tree, Bus with Spurs, and Mixed topologies. The Point-to-Point and Daisy-Chain topologies are possible, but they are not very practical.

Tree Topology

In this topology, one device coupler or junction box connects all of the devices on the segment in a tree like structure. The junction box is connected to the Linking Device with a home-run cable. The length of the brunches (also referred as spurs) can be up to 120 m in length.

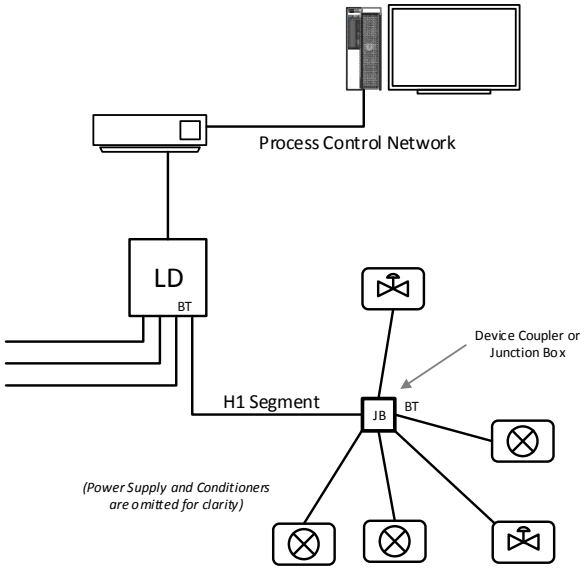


Figure 2.5 Fieldbus H1 Segment.

Two bus terminators (BT in Figure 2.5) placed across the longest run of the segment (also known as the home-run cable). All branches and the home-run cable must add up to 1900 m in length.

Bus with Spurs Topology

The Bus with Spurs has a main trunk referred as the H1 bus and smaller junction boxes to drop one device per junction box with a short spur (1 m to 120 m) stretching across the process area. The terminators are placed at junction boxes to the far ends of the trunk. Figure 2.6 shows a typical bus with spur topology.

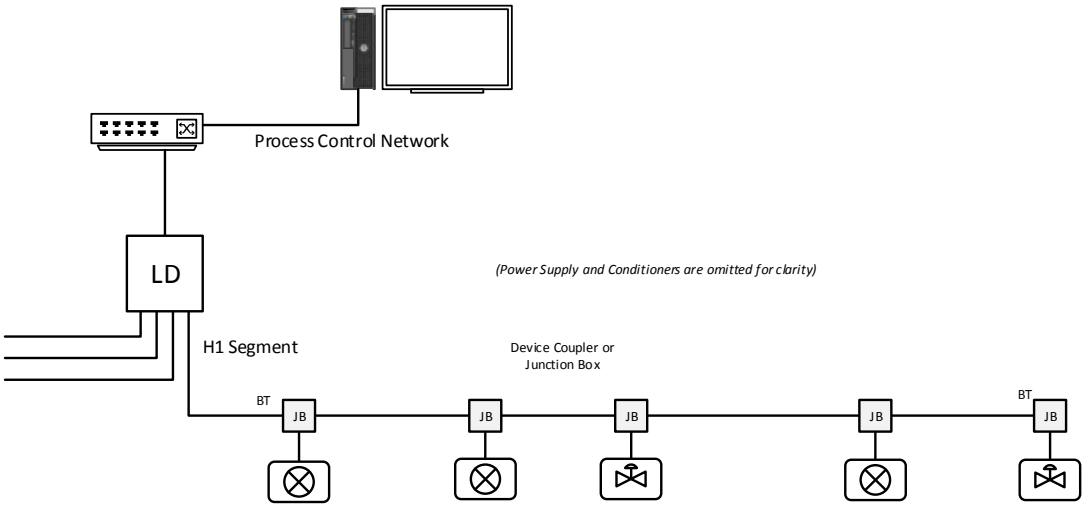


Figure 2.6 Bus with Spur Topology.

Mixed Topology

Short branches produce better performance. It encouraged a mixed type of topology where multiple small tree topologies with short branches spread out in the process area. These trees are connected to a trunk to construct the H1 segment. Figure 2.7 shows a typical mixed type topology.

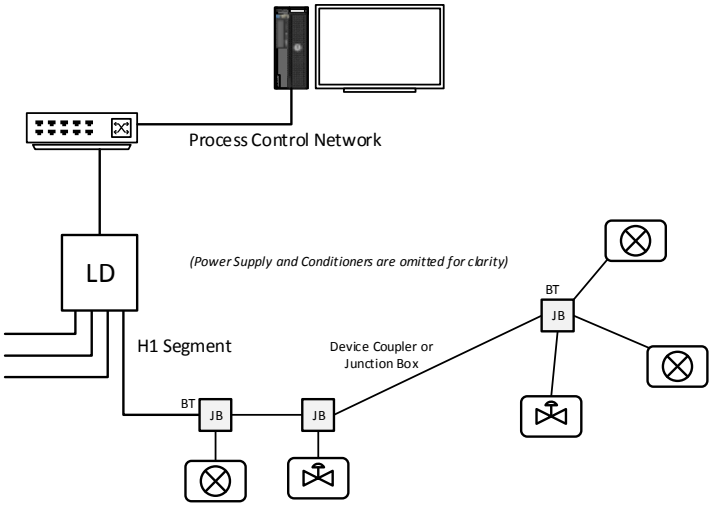


Figure 2.7 Mixed Topology.

2.2 Fieldbus Components and Application

Linking Device

The Linking Device (LD) is an HSE device type that connects the H1 networks from different process areas to the HSE or Process Control Network. They are also referred as Fieldbus Interface Modules by many Distributed Control Systems (DCS). The Linking Devices often support 2, 4, or 8 H1 segments per LD, and typically, deployed as a redundant pair for a set of H1 networks. They also hold the primary and the backup Link Active Schedulers (LAS) for the H1 segments connected to them. They are the gateways to all instruments connected to their H1 networks for configuration or monitoring. Figure 2.8 shows a common connection scheme for a pair of redundant Linking Devices with four H1 networks. The LAS and LD redundancy are covered extensively in the next chapter with the fault tolerance discussions.

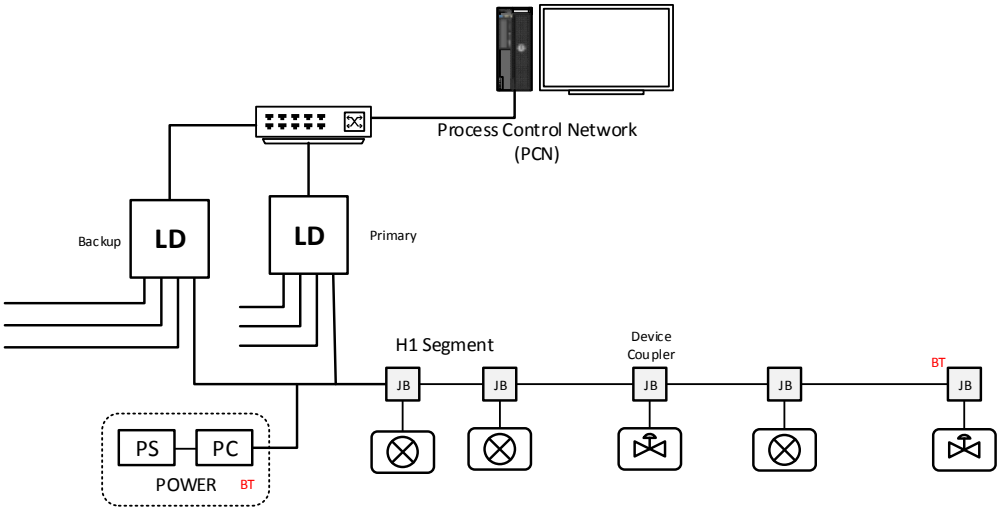


Figure 2.8 Redundant Linking Devices with H1 Network.

Power Supply

The FF Power Supply has two main components – the Bulk Power Supply and the Power Conditioner. Note that, Intrinsically Safe (IS) power and installation details are beyond the scope of this thesis, and only non-IS power supply and installations are discussed. The FF devices generally operate in between 9VDC to 32VDC. The Bulk Power Supply provides up to 32VDC

bulk supply to the Power Conditioner. The Power Conditioners are special power supplies designed in compliance with the IEC 61158-2 standard. They supply an impedance balanced power to the H1 segment while isolating it (segment) from the bulk supply. The Power Conditioner modules are designed to power one H1 segment. The Bulk Power Supply and the Conditioner modules are typically installed in a redundant setup so that, failure of one Bulk Supply or Conditioner may not bring down the H1 segment.

Device Coupler

The Device Couplers or Junction Boxes are a critical part of the FF System deployment. They make it safe to connect or disconnect the FF devices to and from the H1 segment for maintenance without disturbing the communication of other instruments on the same network. They are passive components allowing the FF devices to be connected in parallel to a segment. Figure 2.9 shows a couple of device coupler types with internal circuits. They come in many sizes depending on the number of devices they support. Typically, it has trunk in/out ports along with spur ports for the FF instrument connections. The junction boxes are designed for short-circuit protection so that, one shorted port or instrument does not affect the rest of the H1 segment. Some Device Couplers come with built-in bus terminator (discussed in the following section) essential to complete the H1 segment construction.

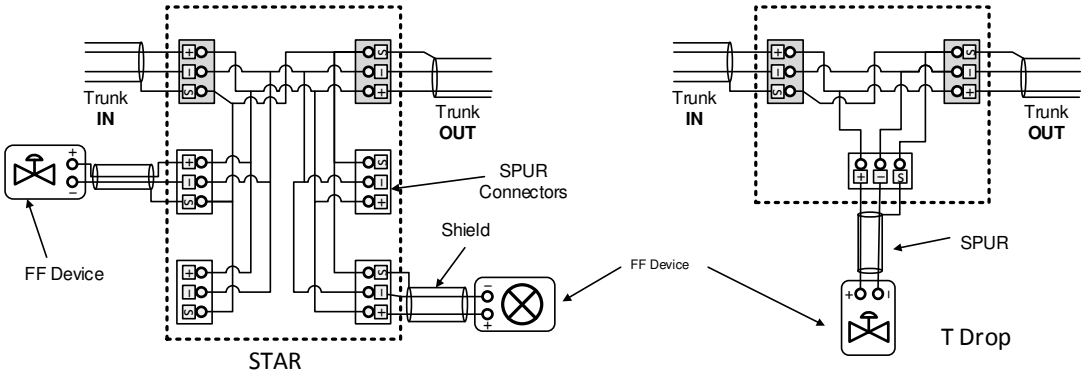


Figure 2.9 Device Couplers - STAR and T-Drop Junction Boxes.

Bus Terminator

The Bus Terminators are simple but required component of the H1 network. There are exactly two bus terminators required for each H1 segment. The bus terminator is an impedance matching module installed at (or near) ends of the longest stretch (Trunk) of an H1 segment. It is essentially a 100 ohm resistor and a capacitor in series as shown in Figure 2.10 to pass 31.25 kbit/s H1 Fieldbus signals. Typically, bus terminators are built-in into the Fieldbus Power

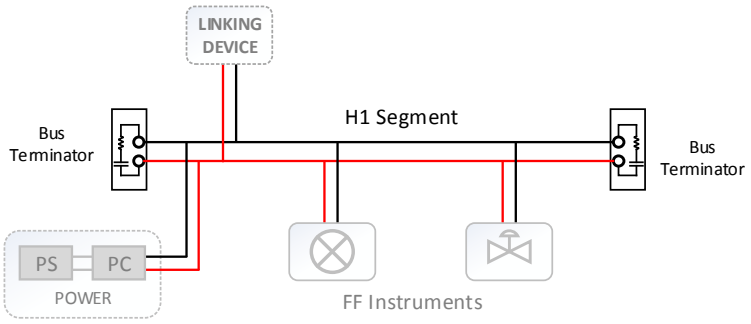


Figure 2.10 Bus Terminators in Segment.

Conditioner or Device Couplers for convenience. They are also available as a sealed module when purchased separately.

Cable

The H1 networks use the same twisted pair cable to deliver both power and communication messages to the devices; therefore, using the right type of cable is a priority. While the cable characteristics like attenuation, characteristic impedance, and capacitance affects the data communication aspect of the application, the size of the cable affects the DC power deliver to the instruments, and together both of these features determine the maximum length of a segment [4]. The IEC/ISA Physical Layer Standard identifies four types of cable to construct the H1 networks or segments as shown in Table 2.1. The maximum length (when trunk and all spurs are added together) of the H1 segment is determined by the cable type, the number of devices on the segment, and the length of spurs.

Table 2.1 Fieldbus H1 Cable Types.

Cable Type	Description	Wire Size	Max. Segment Length
A	Shielded, Twisted Pair	#18 AWG	1900 m
B	Shielded, Multi-Twisted pair	#22 AWG	1200 m
C	Multi-Twisted pair without Shield	#26 AWG	400 m
D	Multi-core, w/o twist, with shield	#16 AWG	200 m

Type “A” cable is preferred as it offers the most protection and flexibility. As a matter of fact, cables manufactured for the FF application are of Type “A”. The intention of allowing the other types (B, C, and D) of cables was that the end users could take advantage of the existing (legacy) wiring to retrofit for a FF system. As long as the length limitations are observed, one could use the existing cable types of B, C, and D to construct successful H1 networks that meets the specification.

FF Devices

The FF instruments or devices are the sensors, actuators, and other measurements devices connected to the H1 networks with the device couplers. They could be classified in various groups based on their capabilities and applications, but from the power consumption perspective, they are classified as 2-Wire or 4-Wire devices. The 2-Wire devices, also referred as bus-powered devices, are those which draw DC power from the H1 network for their operation. They are designed to be low powered devices which typically draw about 12 mA to 20 mA current. The 4-Wire devices are referred as non-bus-powered devices which receive power externally. They do not draw any power from the H1 segment. The FF Devices may also be classified by the type (Input or Output) and the number (single or multivariable) of sensors they process. They are also made to be interoperable with the DD (Device Descriptor) technology and the Host Interoperability Support Test (HIST). From the Data Link Layer capacity point of view, the

devices are also classified as Basic or Link-Master. The Link-Master devices can take the role of a Link Active Scheduler (LAS) for the segment.

H1 Repeater

The Repeater is an *active* device comparable to an Ethernet network Hub. They are designed to extend an H1 network range to another 1900 m by amplifying and correctly transmitting or receiving the FF signal. The Repeaters can be either bus-powered or non-bus-powered, and there can be up to four Repeaters on an H1 network. Each extension after the Repeater is completed with another pair of Bus Terminators. However, all of the extensions of the same H1 network are considered as one logical H1 segment from the application and communication perspective. This is a key component of interest for the solutions outlined in this thesis. Figure 2.11 shows a H1 segment extended four times with four non-bus-powered repeaters. The Repeaters can be used to split a segment into multiple small segments.

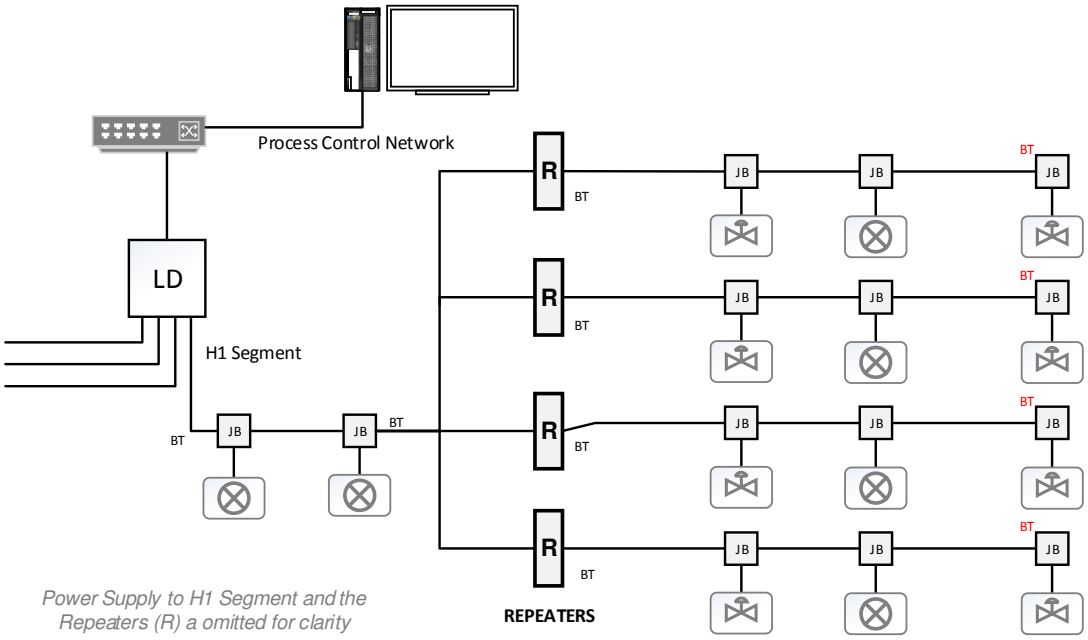


Figure 2.11 H1 Segment Extended with Active Fieldbus Repeater.

Fieldbus Application

The Foundation Fieldbus Application or the User Layer defines high-level function block based programming for the devices and control configuration. Replacing the traditional I/O with a digital I/O was only part of the goals of the Foundation Fieldbus. The technology with its rich function block programming framework, deterministic communication scheduler, and Control-In-Field (CiF) capability makes it a complete process automation infrastructure [1]. The market data related to the FF installations, types of registered FF devices, and the supplier focus makes the technology especially suited for the *continuous* process automation [3].

Function Blocks

The function blocks are the building blocks of FF applications and system configuration. There are mainly two categories of blocks defined – Configuration Blocks and Function Blocks. The Configuration Blocks are used to configure the hardware and vendor specific configurations of a device while the Function Blocks are to configure the applications [5]. The Programming of various function blocks are performed by setting the standardized parameter values. The FF defines one RESOURCE block and one or more (optional) TRANSDUCER block(s) per FF

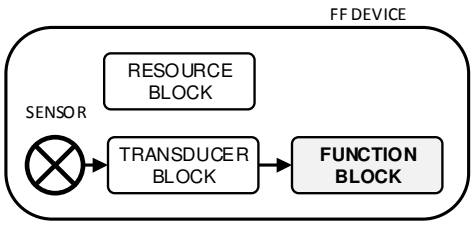


Figure 2.12 FF User Layer Blocks.

device as Configuration Blocks. The RESOURCE blocks acts as the key to all resources available in the device. It specifies the device manufacturer ID, revision, and available functionality of a device. The TRANSDUCER blocks are necessary when one or more sensor is present. It provides the configuration of the sensor type, calibration, etc. of the device. The application Function block logically connects to a TRANSDUCER block for its data. Figure 2.12 illustrates the user layer function block organization of a FF instrument.

Application Blocks

The application (function) blocks are defined by the inputs, outputs, set of parameters, and algorithm they execute to perform the basic automation functions they are designed to implement [6]. A host of Function Blocks are standardized by the FF to encompass majority of the regulatory control, data acquisition, alerts, and alarm functions generally performed by the Distributed Control System. These function blocks reside and execute in the FF devices, and the application designer interconnects relevant blocks into control strategies or modules to perform a control application. The Analog Input (AI), Analog Output (AO), Discrete Input (DI), Discrete Output (DO) blocks are implemented in their respective device types (AI, AO, DI, ad DO). Table 2.2 and Table 2.3 lists the function blocks standardized by the FF for data acquisition and control applications.

Table 2.2 Input / Output Function Blocks.

Block	Function / Application
AI – Analog Input	It is analog data acquisition with signal characterization and alarming. Example: Pressure, Temperature measurement. Connects to an analog input TRNSDUCER for data.
AO – Analog Output	It converts the analog Setpoint (SP) signal for valve or other output device actuation through a TRANSDUCER channel. It also implements the fault state mechanism for fault handling.
DI – Discrete Input	It is discrete data acquisition with characterization and alarm processing. It connects to a discrete input TRANSDUCER channel for data.

Table 2.2 Input / Output Function Blocks (Continued…).

Block	Function / Application
DO – Discrete Output	It converts the discrete Setpoint (SP) signal for solenoid operated devices actuation through a TRANSDUCER channel. It also implements the fault state mechanism for fault handling.
MAI – Multiple Analog Input **MDI** – Multiple Discrete Input	They are same as Analog (discrete for MDI) Input block, except these blocks cluster multiple channels into one function block. Each channel needs to connect to its own analog (discrete for MDI) input TRANSDUCER channel for data.
MAO – Multiple Analog Output **MDO** – Multiple Discrete Output	They are same as Analog (discrete for MDI) output block, except these blocks cluster multiple channels into one function block. Each channel needs to connect to its own analog (discrete for MDI) output TRANSDUCER channel for data.

Table 2.3 Standard Regulatory Control Function Blocks [7].

Block	Function / Application
Standard Blocks	
PID – PID Control	This is a classic regulatory control block with Proportional, Integral, and Derivative regulatory control.
RA – Ratio Control	This is a regulatory control block for Ratio Control.
ML – Manual Loader	Operator or remote algorithm can set the output of this block.
BG – Bias Gain	It is used to add Bias or Gain in a regulatory control path.
CS – Control Selector	This block is used to select one out of three control signals.
PD	This block is Similar to the PID block, but without the integral control.

Table 2.4 Advanced Control Function Blocks [7].

Block	Function / Application
Advanced Blocks	
DC – Device Control	It is a discrete device control block with multiple states
OS – Output Splitter	This is a regulatory control block to perform split-range controls.
SPG – Setpoint Ramp Generator	This block generates profile based Setpoint Ramps to be used by the regulatory control or other function blocks for calculation.
SC – Signal Characterizer	This provides non-linear function based signal characterization.
LL – Lead Lag	This is a calculation block to add lead/lag behavior to a signal.
DT – Deadtime	This calculation block can add delay to a continuous signal.
INT – Integrator	This is a calculation block used to totalize a process value.
ISEL – Input Selector	This calculation block can select from four possible input signals based on desired algorithm (First Good, Max, Min, etc.)
ARTH – Arithmetic	This is a calculation block with some commonly used algorithm.
TMR – Timer Block	This calculation block can provide a timer/counter function.
AALM – Analog Alarm	This is calculation block to provide alarm condition reporting.

Another advanced type function block defined as the "Flexible Function Block" (FFB) to address logic implementation that allows the IEC 1131 Logic implementation. The FFB complements the capabilities enabled by the Input /Output, Regulatory, and Calculation function blocks (Table 2.2, 2.3, and 2.4), and together, offers a complete control platform for the process automation. The function blocks are connected together like "*lego*" to build control strategies graphically. Figure 2.13 shows some examples of basic control strategies used for regulatory control.

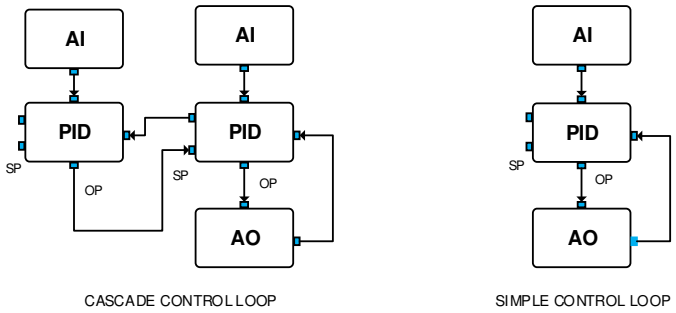


Figure 2.13 Fieldbus Control Strategies.

Control In Field (CiF)

The Regulatory control and calculation Function Blocks could be implemented in any FF devices if the devices support these block. The blocks could be distributed across multiple devices for load balancing and control efficiency. At this point, it is sufficient to understand that the strategies in Figure 2.13 could be arranged so that, different instruments execute and handle portion of the control and update their respective links through a deterministic mechanism called publishing / subscribing. The link scheduler ensures that each link is updated on a fixed time interval to produce the desired control function. For example, the cascade control loop in Figure 2.13 could be a temperature control application that controls the flow of steam through a heat exchanger, which in turn controls the temperature of a product.

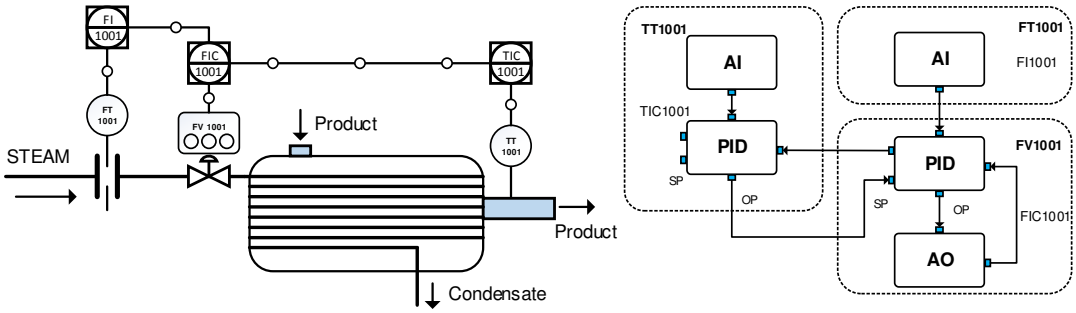


Figure 2.14 Control in Field Devices (Cascade Loop).

The temperature controller in this application is considered as the master controller, while the flow controller is the slave or secondary controller [8]. The flow controller receives its Setpoint (SP) from the temperature controller and controls the steam valve to maintain desired

temperature of the product. Figure 2.14 shows the same cascade control loop with distributed function blocks among three FF devices (TT101, FT101, and FV101).

Together, three control modules in the FF devices operate the temperature control loop independent of a central controller. Therefore, the control is no longer centralized but distributed in the Field, hence *Control in Field* or CiF. The CiF is unique to Foundation Fieldbus, and a critical enabler of the single loop integrity, which had been highly desired by the industry for increased system availability. The CiF increases overall system reliability by reducing the number of components required for the same application, while reducing the overall communication data between the instruments and the central controllers [9]. With the control being distributed across the plant floor, a truly distributed control system is established with unprecedented scalability.

Fieldbus Schedule and Link Active Scheduler

The function blocks are carefully linked and then assigned to the FF devices during configuration and commissioning of the segments. A detailed time schedule is constructed for each segment during the configuration time defining exactly when each function block is executed in their respective devices, and when to publish the link-data on the segment for the subscribers. The function block executions and communication on an H1 segment is controlled by this schedule, and each Link-Master enabled device on the segment has a copy of this schedule. The Link-Master executes the schedule on a *macrocyle* to include enough time to execute the function blocks, publish links, and respond to supervisory request (configuration, monitoring, etc.). There can be multiple Link-Masters enabled devices on the segment for redundancy.

The Link-Master in-charge of the schedule at a given time is called the Link Active Scheduler or LAS for that segment. The Primary and Backup Linking Devices (LD) connected to the segment typically has the role of the primary and secondary LAS for the segment. The field devices supporting Link-Master functions could as well be configured as a Backup LAS (BLAS) for the segment they are connected to. The BLAS is another level of redundancy so that, even if both Linking Devices fail, the BLAS device can still manage the schedule and keep the control

function intact as long as the segment has power. The Link Active Scheduler uses a token to control when each device on the segment should execute blocks, transmit link, alarm, alert, and other supervisory data. A device may execute and put data on the bus only after it receives the token from the LAS. The token is returned back to the LAS after the device completes its task [10, p. 9]. This process is exemplified in Chapter 4 during the prototyping and data analysis.

2.3 Value Proposition and Challenges

As an open all-digital technology, the FF incorporates key aspects of the *Collaborative Process Automation System* or CPAS. The CPAS is the next evolution of Process Automation System defined by ARC (an advisory group to the industry) as an automation system with the following features [11]:

- Extraordinary Performance
- Continuous Improvement
- Proactive Execution
- Common Actionable Context
- Single Version of the Truth
- Automate Everything that Should be Automated
- Facilitate Knowledge Workers
- Common Infrastructure Based on Standards.

The two-way digital communication mode provides reliable data. The data is digitized at the source and travel with the status all the way to the supervisory system. With the quality and status, data become more meaningful to the operators. The control data is made deterministic with the Publisher/Subscriber mechanisms. The FF enables more diagnostics data from the instruments about their health, which leads to an expanded view of the process when compared with traditional IO based system. The reduction of cable, hardware, and communication data when deploying the CiF lead to a more reliable system.

Challenges

The Foundation Fieldbus requires a paradigm shift in planning, designing, and deploying automation and control system to achieve most of its benefits. It is evident in the industry that, the adoption of this technology, though in growing acceptance, is not as wide-spread as it was originally predicted. Even when the FF is accepted as install-base it is deployed as a digital IO network, not to its fullest potential. One of the perceptions of this technology is that, since it is a serial communication, and multiple process values are monitored and controlled with one pair of cable (H1), a break or failure in the trunk of the H1 segment could cause a *loss of view* of the process. The L*oss of View* is one of the worst situations that can happen to operators during plant operation.

Though there are different levels of redundancies, fault tolerances, and fault-state handling mechanisms are available in the FF to lessen the impact of such a failure, the fear itself is real since the H1 physical layer does not have cable redundancy for the trunk [12] [13]. Potential effects of a break in the segment trunk of a typical system (Figure 2.15) are as follows:

- The break in the H1 trunk could cause all devices on that segment to lose power and become offline (out of service). Extend of the damage would depend on the topology of the network, the location and quantity of power supply, and the location of the LD connection to the segment.
- Since one pair of wire brings in multiple instrument or valve data, the failure in one pair of wire could affect more than one process loop.
- Partial or complete *loss of view* may occur.
- Loops running the CiF may shed to failure mode depending on the location of the break.

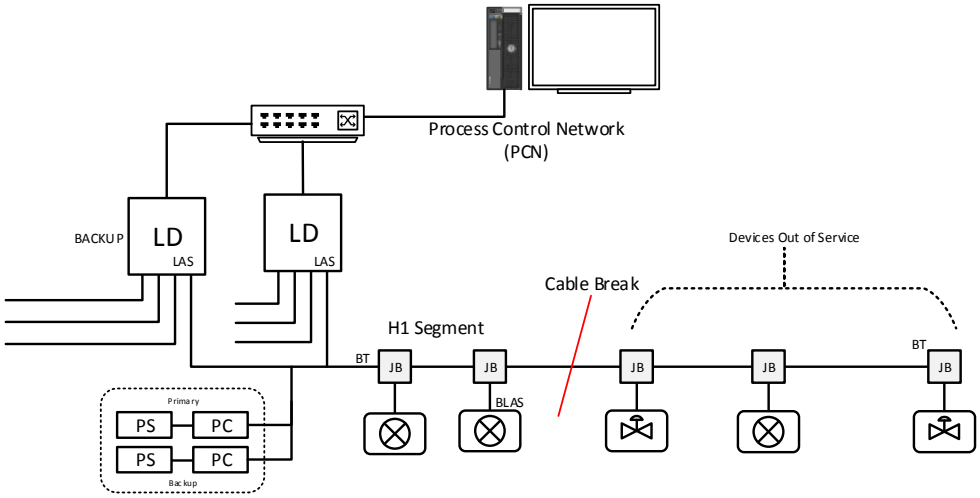


Figure 2.15 Media Fault on H1 Network.

The challenges outlined in this section are critical to the successful deployment of FF Control Systems. However, resolution to this physical layer challenge by improving the fault tolerance and reliability of the network would change the overall perception and confidence of the end-users and integrators. Having a more reliable H1 segment would encourage more of the CiF implementation producing a more available system. Therefore, in this thesis, the challenges of achieving media redundancy on the H1 network are investigated, and a topology framework is evaluated for the efficacy of fault tolerance on the H1 physical layer network. Following chapter describes various levels and methods of achieving fault tolerance with the Foundation Fieldbus. It also covers works by other product vendors to address the media redundancy for the H1 networks.

3. Fault Tolerance

The redundancy of various FF components, architecture, and control strategies are naturally built into the Foundation technology. In general, hardware components are simply doubled up with primary and backup roles so that, if one fails, other will continue to operate. Even though the H1 network does not have cable redundancy, there are ways to increase availability within the H1 system through first identifying the most likely points of failure, and then applying the redundant control strategy concepts through duplicating the hardware or controller blocks. The flexibility in the FF technology empowers the system engineers to find the most appropriate solution to a particular application [14]. The focus of this thesis is to mitigate any fault resulted from a break in the H1 segment. Therefore, the discussion is limited only to the extent of those faults. Following sections outlines various redundancy schemes available.

Redundancy in Fieldbus System

The Linking Device and Power Supply redundancy for the H1 segments are achieved by simply doubling up the hardware. The Primary and Backup LD ensure at least one of them is available to connect the H1 segments to the Process Control Network for supervisory data access. Figure 3.1 shows a LD, Power Supply, and LAS redundancy *typical* for a FF H1 system. The redundant bulk power supply and the conditioners ensure backup power if one the pair fails. Keeping the segment alive with power is critical even if there are failures in the segment that compromise parts of the network, so that the fault-state handling could be initiated. The battery or UPS backup of the bulk power supply can add an additional level of redundancy for the power into the segment. The LAS redundancy is equally critical since it is the master scheduler of the segment. The Linking Devices typically manage multiple segments as a cluster. They are the default *primary* and *backup* LAS for all of the H1 segments attached to them. Each LD is perceived as another FF device on the H1 segment by the other devices.

A third level backup LAS can be placed in one of the FF devices in the form of a BLAS. This allows the segment to continue to operate independent of the LD as long as the power to the segment is intact. Of course, there will be a complete *loss of view* at the operator's station if both LD are at fault. This is true even if the power to the segment is intact. With the BLAS and power

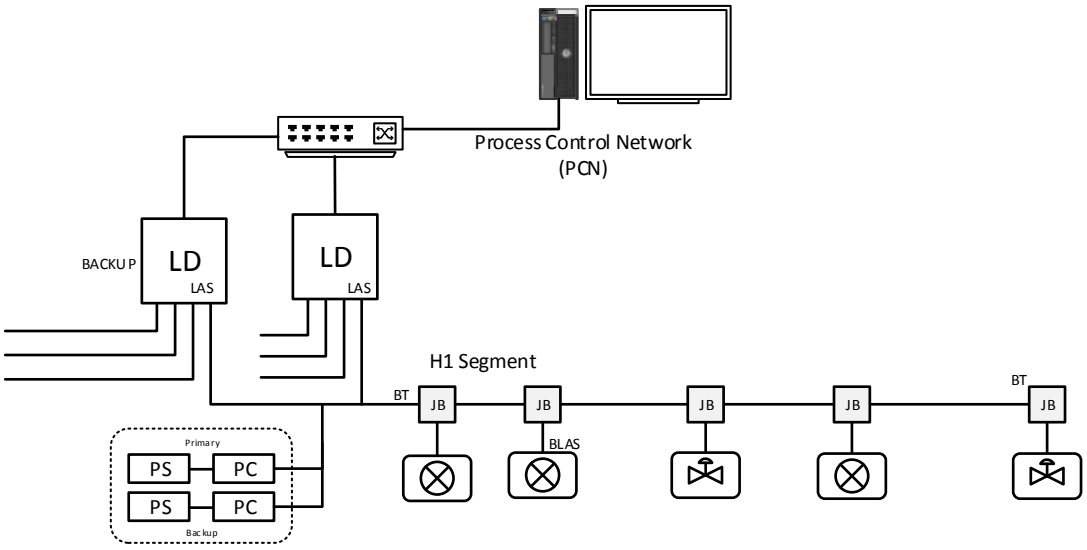


Figure 3.1 LAS and Power Redundancy.

being intact, the devices would continue to operate and execute any CiF configured among them without any interruption to the process.

3.1 H1 Media Redundancy

Though the Foundation Fieldbus H1 does not include specifications for the media redundancy, a direct work-around to mitigate the deficiency had been slow to develop. Instead, alternative redundancy concepts are suggested to minimize the impact of media failure to a particular application [14]. Engineering best practices are established to minimize risks from not having the fault-tolerant physical layer network. Some of these best practices involve reducing the number of instruments that could be put on one H1 network as well as classifying and distributing the instruments according to their process criticality factors [5]. This does not mean

that no work was done on the subject; in fact, work from some Fieldbus peripheral suppliers addresses this issue toward some working solutions.

Moore Industries' Fault-Tolerant Segment

Moore Industries offers a solution involving running dual trunks into the field from the redundant Linking Devices in the form of a U-shaped segment via redundant power conditioners as shown in Figure 3.2. The segment holds exactly one device coupler with in a tree-topology. The power conditioners and the device coupler support automatic bus termination. The terminators are enabled in the power conditioners during the normal operation, but if one of the trunks to the coupler breaks, the termination is switched off from the failed side power conditioner at the same time preventing power and communication on the failed side of the trunk

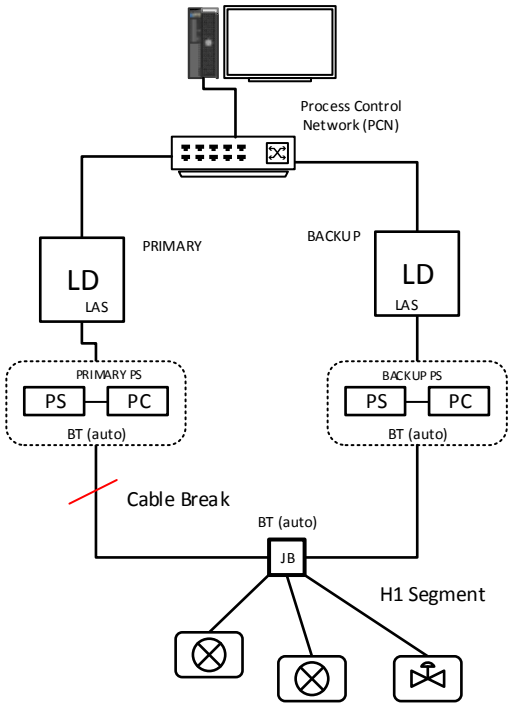


Figure 3.2 Media Redundancy by Moors.

[15] [16]. This keeps a complete segment with exactly two terminators while the power and access to the LD is intact. Figure 2.2 illustrates this concept. This solution adds desired fault-tolerance to H1 media, but this works only for a tree topology with exactly one device coupler. The Bus with Spurs or Mixed topology has more than one device coupler in a segment, and if the

cable break is at the trunk between the device couplers, it may render the segment into two separate partially operational sub-networks; it will not guarantee uninterrupted control and view.

Rockwell Automation

Rockwell has an approach similar to Moors, but their solution is more tightly integrated with their Linking Device features. Generally, they can run two redundant segments all the way across from one end to the other end with the intelligent junction boxes (Device Couplers) to achieve media redundancy for the H1 fieldbus. These Linking Devices has integrated power conditioners/supply for each of the segments. Any solution must use proprietary device couplers and linking devices from Rockwell to design the parallel redundancy networks. This approach of achieving redundancy may limit the total length of segments since parallel segments could cut away from the 1900 m segment cap specified by the FF. The segments on Rockwell linking devices may as well be used as independent segments without the media redundancy, i.e., without forming as one fault-tolerant segment.

3.2 Proposed Fault Tolerant Architecture

The *Loss of view* and *loss of control* are two key concerns emerged from the FF system design and deployment. These concerns, though sometimes perceived, are very real, and their impact to the process depends on how a particular system's fault tolerance is designed regardless of the control being implemented in a central controller or in the field. If the controls are distributed into the FF field devices on a segment designed with current engineering best practices but with no media redundancy, when the trunk cable breaks, the best one can achieve is a safe shutdown of the process. This is achieved by providing the redundant power to segment from both ends of the segment and careful configuration of the instruments for fault-state actions. In such a system, there will definitely be a total *loss of control*, and it may or may not face a *loss of view* depending on the capability of the particular Linking Devices used. The aim of this thesis is to achieve uninterrupted control (CiF) and communication, even when there is a break in the

main trunk cable. The uninterrupted communication includes both scheduled and unscheduled traffics; so that, any control being executed in the central controller (not CiF) continue to operate without shedding, and at the same time the supervisory data acquisition service remains intact. This will eliminate concerns of the *loss of control* and *loss of view* from the H1 segment breakage completely and increase the overall system reliability.

The FF is designed to be robust and resilient under many circumstances. Let us perform an exercise to understand how a system engineer may simply design a better network to mitigate many of the potential effects of a cable break on the H1 network. It is evident from examining the architectures in Figure 3.1 and Figure 3.2 that, the backup Linking Device and the Power Supply could be rearranged so that, they tap at the ends of the segment (instead if both connecting at the same end), and produce a U-shaped segment similar to what Moore Industries uses for their solution. Let us see if any benefit is gained from making *only* this *one change* of rearranging and no other enhancements to the segment (Figure 3.3).

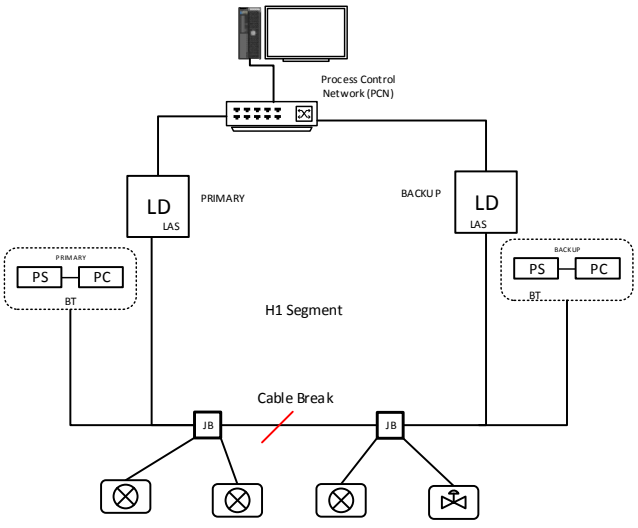


Figure 3.3 U-Shaped Segment with No Enhancement.

One or more of the following outcomes will follow:

- The segment will split into two networks, and the devices will split between them depending on where the break was. The devices would still be operational since the

new networks will still have power. So, the fail-safe states are assured. However, there will be a terminator missing in each new network.

- The primary and backup Linking Device will become the LAS for each new network. The lack of a terminator could cause the FF messages to be distorted a bit, but unless there is lot of noise, most of the devices should still be talking to the LAS. This means the supervisory system may be able to receive data from both Linking Devices to cover all instruments on the original segment. This however is subject to the capabilities of the Linking Device in terms of their capacity of redundancy handling.
- If a single enhancement of auto-bus-termination is added to the network in Figure 3.3 by adding device couplers with automatic bus-termination capability, the fieldbus message quality on each of the partial networks could be reassured, and by doing so the *loss of view* is made non-existing since the primary and backup LD would respond to the supervisory system's request for the process data. If two devices were part of the same CiF loop, and they fell into the same side of the broken network, it would continue to operate as if there were no fault at all. The backup LAS (from the backup LD) would ensure that the loop is executing on its macrocycle. If the devices participating in a CiF loop but get separated in the broken networks, the controllers would shed safely since they would be programmed to do so (typical of control schemes). The operators wouldn't have lost the *view*, and they could be operating manually until the network is restored.

Though the scenarios described above kept almost all of the functionalities except the CiF across the broken network parts operational, it is still subject to the capabilities of a particular host system or Linking Device used. Keeping the remaining functionalities intact (uninterrupted) is yet to be achieved, and this could only be realized by implementing functional redundancy on the segment.

Recall the FF component "Repeaters" described in Section 2.2. They are functionally similar to active "hubs" used in the computer LAN, but these are designed for the H1 network passing the FF messages. In an H1 network construction, the Repeaters extend an existing segment into new segments which works as if they all belong to the same H1 segment. What if one of the broken network parts could be turned into an extension of the original network before any of the fault being registered? Wouldn't that kind of solve the problem? A *Dynamic Synchronization Repeater* (DSR) circuit could be added across the primary and backup LD, and activated automatically when a cable break is detected. The DSR transforms the broken network into an extension of the original network. The system must first detect the break on the segment and initiate the DSR quickly.

Fault Detection

The roles and locations of the primary and backup Linking Devices lent themselves as the

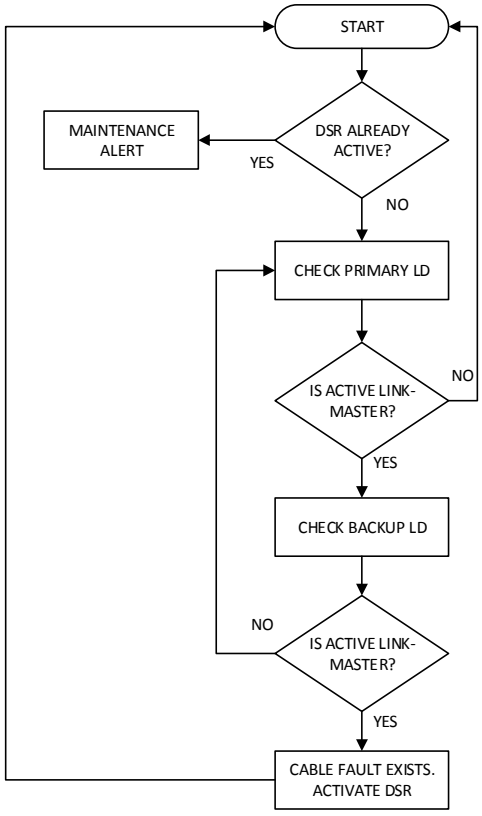


Figure 3.4 Segment Break Detection Algorithm.

ideal place to detect the cable fault for the U-shaped H1 segments. As the primary and backup Link-Masters of the segment, both LDs (Figure 3.3) keep track of all devices on the segment by maintaining a so called “live list”. Assuming a the U-Shaped segment is used (illustrated by Figure 3.2 and 3.3) to power and the LDs are connected to the edges of the segment, adding a communication link between the primary and backup LDs would allow them to run an algorithm and detect the cable fault. The communication link between the LDs is necessary to differentiate between the cable fault and LD failure. At a cable break, both LDs would assume the role of active Link-Master of their respective broken segment, and even with one missing terminators on each side, they would be able to identify the devices live on their segment. The fault detection task is handled by the LD with active Link-Master, and it is automatically assigned by the detection algorithm. Figure 3.4 shows algorithm for the fault detection. The Linking Devices are typically installed near each other. In fact, most of the time they reside in the same instrument cabinet. This close proximity makes it appropriate for the DSR module to be implemented within the LDs, and then interconnect them with a synchronizing channel, or as a separate module residing in the same instrument cabinet interconnecting both LDs through a synchronizing channel. Following sections elaborates the design components for such a solution.

Dynamic Fault Correction

An enhanced FF Repeater called *Dynamic Synchronization Repeater* or DSR is proposed. It monitors the active and backup Link-Masters on the network to detect the cable break on the H1 segment, and if a break is detected, it restore the segments communication by attaching the segment (broken part) belonging to the backup Link-Master back into the original segment as an extension of the original. A simplified overview of a DSR attached to an H1 segment with redundant LD is shown on Figure 3.5. Typically, the DSR would also implement the fault detection algorithm. In this example an H1 segment with two Device Couplers is presented. During normal operations, the JB1 and JB2 junction boxes have healthy connection between them. When the connection between the JB1 and JB2 is broken, the DSR detects it by identifying

the primary and backup LDs running LAS as the "Active" Link-Masters (algorithm on Figure 3.4). Table 3.1, 3.2, and 3.3 list the chronological events and states of different components during the normal operation, at fault, and at restoration by the DSR. The status of the redundant power supplies is not included in the table since they remain active throughout the events.

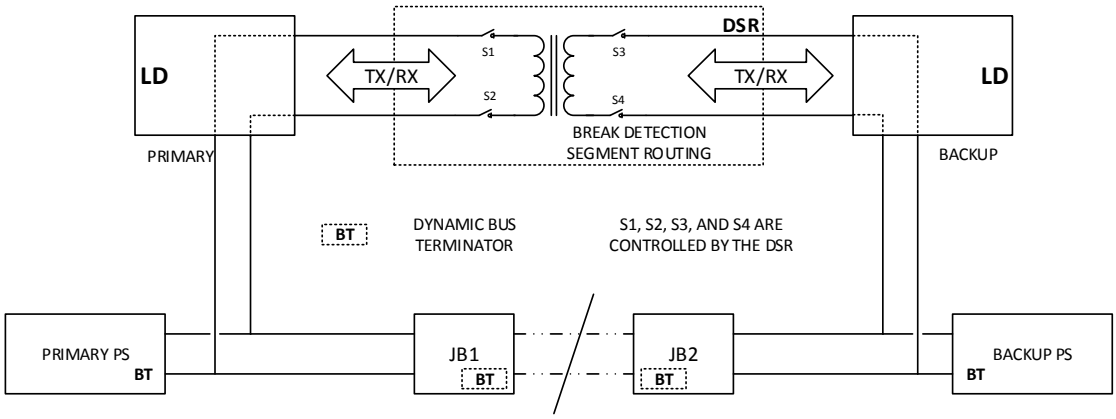


Figure 3.5 Proposed Solution Architecture with DSR.

Table 3.1 Normal Operation (JB1 and JB2 are Connected Through Normal Trunk).

Device Couplers (JB1, JB2)	Primary LD (LDP)	Backup LD (LDB)	DSR
The dynamic BT at JB1 and JB2 are inactive.	The LDP has "active" Link-Master role, and it is responsible for all bus communication.	The LDB has "backup" Link-Master role, and it is standing-by. It has a copy of the schedule.	The DSR monitors the LDP and LDB's Link-Master role continuously.

Table 3.2 FAULT Active (Connection Between JB1 and JB2 is Broken).

Device Couplers (JB1, JB2)	Primary LD (LDP)	Backup LD (LDB)	DSR
The dynamic bus terminators (BT) at JB1 and JB2 are Activated.	The LDP is "active" Link-Master on one segment with missing devices from *live-list*.	The LDB is "active" Link-Master on the other segment with missing devices from *live-list*.	The DSR identifies cable break by detecting LDP and LDB both running as "active" Link-Masters.

Table 3.3 Segment Restoration (Link Between JB1 and JB2 is Broken; Routed Via DSR).

Device Couplers (JB1, JB2)	Primary and Backup LD (LDP, LDB)	DSR
The dynamic bus terminator (BT) at JB1 and JB2 are active.	The LDP and LDB sees each other back on the segment, and one of them drops out of the "active" Link-Master role. The segment starts to operate normally with the entire *live-list* of devices.	The DSR activates its repeater circuit and routes the FF signal across its channels from the left to the right network by activating S1 through S4, and essentially, turning the right network into an extension of the left network.

Whether or not the devices would register as missing from the *live-list*, or a broken FF link in the CiF strategy during a cable break depends on how fast the DSR circuit can react to restore the connection. In all likelihood, the supervisory system and the control network would not experience any interruption in its operation.

Automatic Bus Termination

For the DSR to work successfully, the device couplers must be able to automatically terminate at the faulty end. This will ensure at least two terminators present at each broken segment to conform to the H1 specification. Typically, permanent terminators shall be installed at the primary and backup power supply conditioners. Specific auto-termination circuit and its implementation are not discussed in this thesis; it only focuses on their application as enablers of the DSR technology. It is worth noting that, there are a few off-the-shelf models of device couplers available with such features.

3.3 Dynamic Synchronization Repeater (DSR)

The Dynamic Synchronization Repeater (DSR) is proposed as an active Fieldbus Repeater with an embedded controller to run the cable fault detection algorithm outlined in Figure 3.4. Essentially, it would have to be a passive FF device with the capacity to read and decode the FF messages from the H1 segment to determine the address of the "Active" Link-Master's (LAS). The embedded controllers and other peripheral components are necessary to construct a device capable of detecting and decoding the FF messages. The FF messages are composed of data from different layers of the protocol similar to the TCP/IP protocol messages encapsulated in the Ethernet datagrams. The Fieldbus messages include the Data Link Layer (DLL), Fieldbus Access SubLayer (FAS), Fieldbus Message Specification (FMS), and System Management (SM) part [17]. Without getting heavily into the actual FF H1 protocol specification, the basic composition of a FF message could be described as outlined in Figure 3.6.

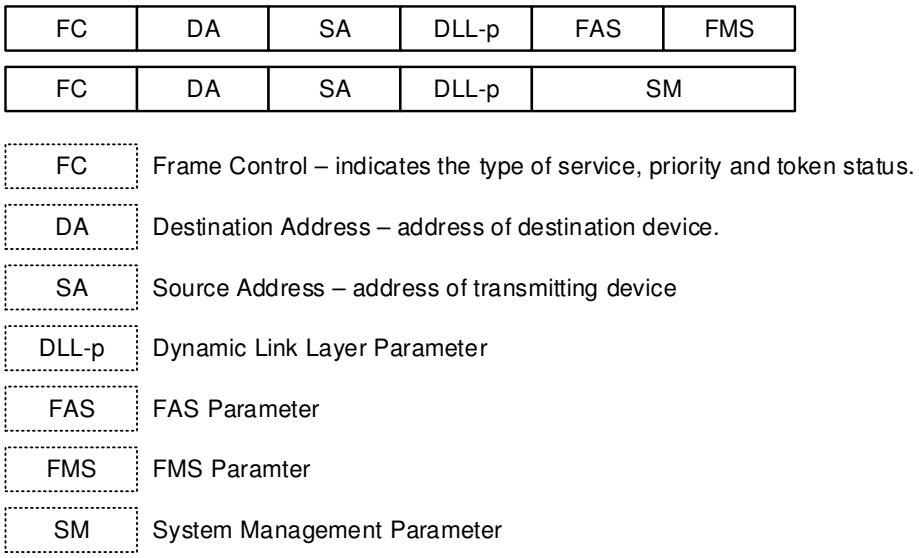


Figure 3.6 Fieldbus Message Structures.

The DSR must be able to read these messages and decode. For example, to determine the LAS or "active"' Link-Master's address on the segment, DSR would look for a message encoded for the Time Distribution (TD) since only the LAS may be able to send the time distribution on

the segment [17]. A sample message of the LAS Time Distribution message is shown in Figure 3.7 where hexadecimal value 0x11 represents the TD type DLPDU (Data Link Protocol Data Unit), and the source address 0x10 is the actual address of LAS device.

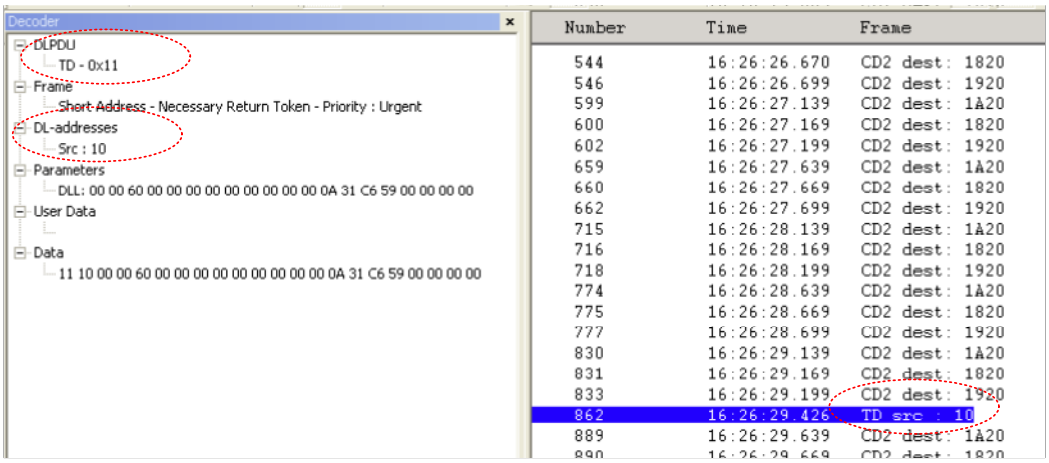


Figure 3.7 FF Message of LAS Time Distribution (Captured and Filtered for LAS).

The system architecture of such the DSR device includes a Medium Attachment Unit (MAU), Foundation Fieldbus Communications Controller (FFCC), Fieldbus Repeater Unit (FRU), and of course the CPU (Figure 3.8). The MAUs attach the device on to the FF segment on two points at the LDP and LDB ends. The Fieldbus Communication Controller performs the FF message decoding.

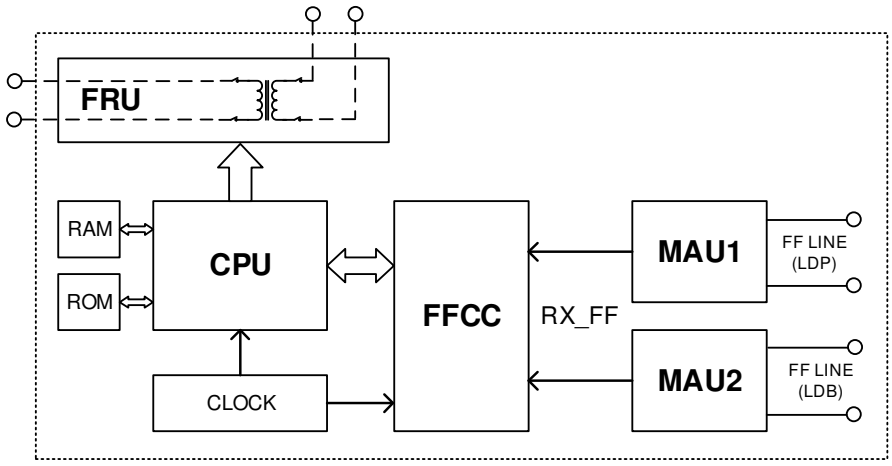


Figure 3.8 Conceptual DSR System Architecture.

4. Prototyping and Analysis

Off-the-shelf hardware and software were used to devise a functionally equivalent prototype DSR. It was then integrated into a fully redundant H1 test segment with redundant power supplies, redundant Linking Devices (LDP and LDB), and multiple FF devices running a real-world application as Control-in-Field (CiF). A real-world cascade temperature control loop was implemented in the FF devices (CiF). The steady-state operating parameters were recorded and analyzed to establish the baseline of the normal operation. A segment break was induced to simulate the target segment fault. The FF messages and signal traces were collected to establish fault-state behavior of the test segment. The DSR was then activated to mitigate cable break and see how the control and communication functions were restored. Additional testing was performed so that the fault is mitigated automatically without any pause to verify the uninterrupted control and communication function of the test segment and its application. As predicted, proposed DSR segment topology based solution appeared to be maintaining uninterrupted control and communication with no loss of control or view. The FF Messages and signal traces were captured and recorded to support this outcome.

DSR Apparatus

A standard off-the-shelf Fieldbus Active Repeater (model: RP312) module was integrated within the redundant H1 segment via toggle switches. The toggle switches were placed strategically so that, the repeater is completely inactive until the switches are turned on. The toggle switches with multiple poles were used so that, all of them could be turned on/off at the same time as it would be if it were an embedded DSR system. The RP312 has a simple wiring configuration that comes with an integrated bus terminator on the external network, which eliminated the need for one of the device couplers used in the system to have the auto-bus-termination. The wiring diagram for the RP312 Repeater with switches is shown in Figure 4.1. It

shows the switches and RP312 wired into a terminal block assembly which is then integrated into the test system.

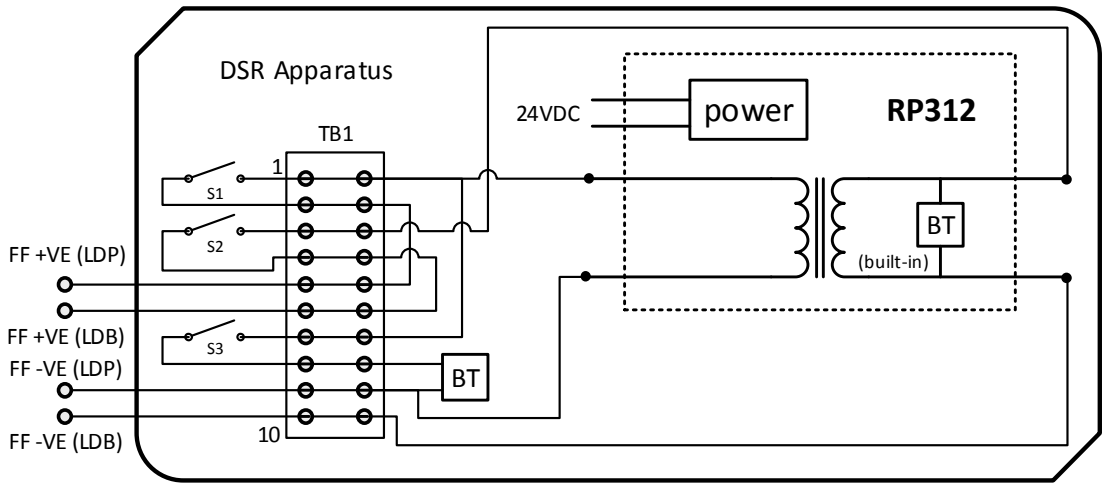


Figure 4.1 DSR Equivalent Wiring Diagram.

The switches S1 and S2 were used to activate the repeater, while switch S3 is used to activate one of the additional terminators needed during the segment break. The apparatus described by Figure 28 is connected to the H1 segment under test using terminals *+veFF(LDP)*, *–veFF(LDP)*, *+veFF(LDB)* and *–veFF(LDB)*. Only the positive wire from the LDP and LDB are switched through (S1 and S2) while the negative terminals are connected directly to reduce the number of manual switches to be operated during this experiment. Even with the negative terminals connected, the repeater circuit stays fully inactive during the normal operation. Note that the Active Repeater requires a 24VDC source for power stabilization of the output signal, which was supplied continuously throughout various experiments.

4.1 Test System

A fully redundant system was constructed using a pair of Fieldbus power supply with conditioners and Linking Devices. Each power supply and conditioner set has a built-in bus terminator. When placed in redundant settings of a fieldbus segment, they fulfill the requirement

of exactly two terminators per segment. The Primary (LDP) and Backup Linking (LDB) Devices are connected on each end of the segment to construct a U-shape network. The DSR apparatus was integrated near the Linking Device level as described in Figure 4.2. It was critical that the proposed apparatus was installed near the LDP/B ports to keep the spur length between them through the DSR at a minimum.

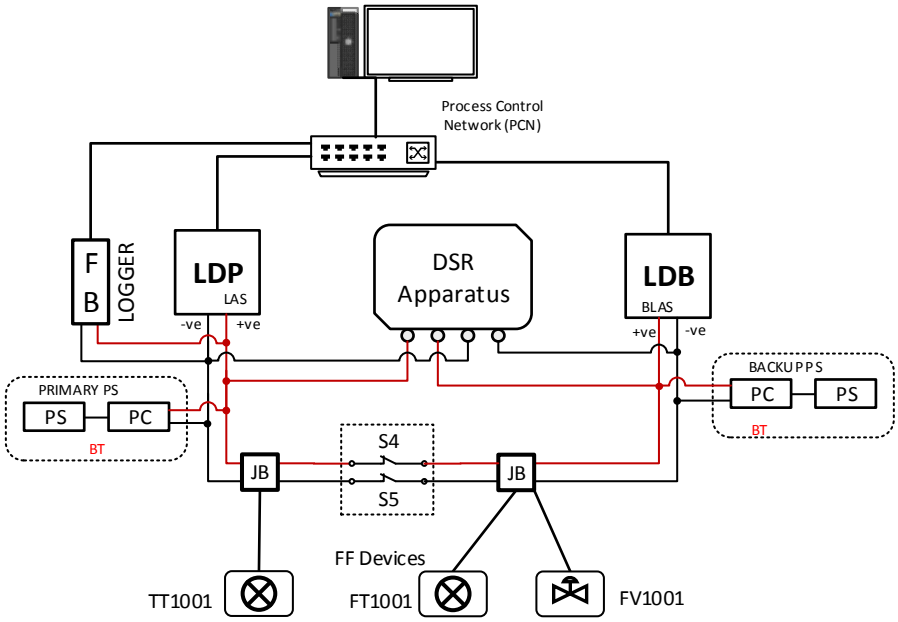


Figure 4.2 Test System with Segment Under Test.

H1 Segment under Test and Test Application

Two device couplers were used in the segment so that a break between them could be simulated to demonstrate a realistic trunk break. The switches (DPDT) S4 and S5 are attached between the device couplers to induce the break. A FB (Fieldbus) Logger was also installed to collect the FF messages from the segment during testing. The logger works by sniffing the FF packets from the segment and sending them to the engineering workstation for storage and analysis. The packets captured by this device would be used to validate findings. It is worth noting that, the segment illustrated in Figure 4.2 does not represent the segments' true scale in terms of length, and the LDP, LDB, and the DSR would typically be in close proximity. They

might even be in the same instrument cabinet. Therefore, the length of wirings between the LDP/LDB and the DSR is nominal, and could be ignored for the overall FF segment length calculation.

A real-world application was configured (described in Figure 2.14, section 2.2) in the segment using three FF instruments. A temperature transmitter (TT1001), a flow transmitter (FT1001), and a valve actuating device (FV1001) complete the application. Figure 4.3 shows how the control application and the function blocks are distributed across these three devices. The links with dotted line represents the external (to the device) data links updated by the publishing/subscribing mechanism that is scheduled and maintained by the LAS. The health of these links is critical for the control strategy to function properly. They were monitored throughout the experiments to evaluate the state of control.

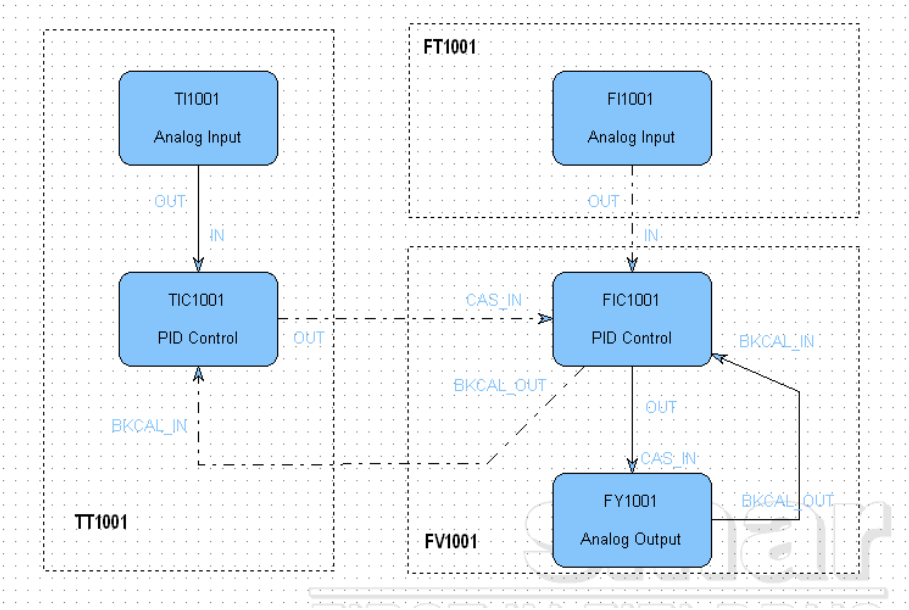


Figure 4.3 FF Application (CiF) Running on Test System.

Engineering and Supervisory Station

The role of the supervisory workstation in Figure 4.2 for this experiment was to configure, update, monitor, and log FF packets on the test system. The software tools on the workstation used to reconfigure and monitor live data from any of the FF devices on the test

segment. Three types of test data were collected during the experiment and testing. A direct screen capture from the supervisory software tools recorded and indicated the FF configuration state, the FF Message packets from the FB data Logger utility to monitor the communication exchanges between various components, and the oscilloscope traces of the FF messages' electrical characteristics. The screen captures are used to establish references of the configuration and record detail function block behaviors. The FF Packets are analyzed to understand the interactions between the devices at the data link level so that, they can be differentiated between scenarios when the CiF was functioning correctly and incorrectly. The electrical signals traces captured by the oscilloscope were used to establish steady-state baseline for healthy segments with the correct number of terminators verses too many or too few terminators, which is the case if the trunk was broken without any redundancy.

4.2 Normal Operation

The test segment was fully connected, and the instruments were downloaded with their respective configuration for the Control-in-Field loop. Figure 4.4 and 4.5 shows the loop's normal operation including the *live-list* of the instruments on the segment. In this list the LDB with "*" is indicating that it has the role of the LAS while LDP is standing by.

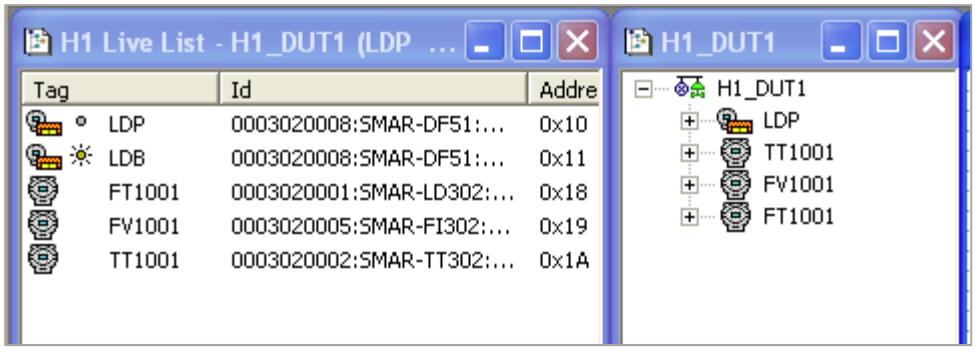


Figure 4.4 Test Segment Live-List Under Normal Operation.

Notice the address column on the far right of the live-list. These addresses are in the hexadecimal number format, and they were used in the FF packets analysis to determine how the

CiF was functioning or which LD was the LAS. For a healthy segment (1000ft long) with exactly two terminators, the expected peak-to-peak FF signal is about 800mV [5]. The normal operation indicated around 900mV of signal which was perfectly normal given that the segment length was nominal. Figure 4.5 shows the oscilloscope's capture of this normal operation signal.

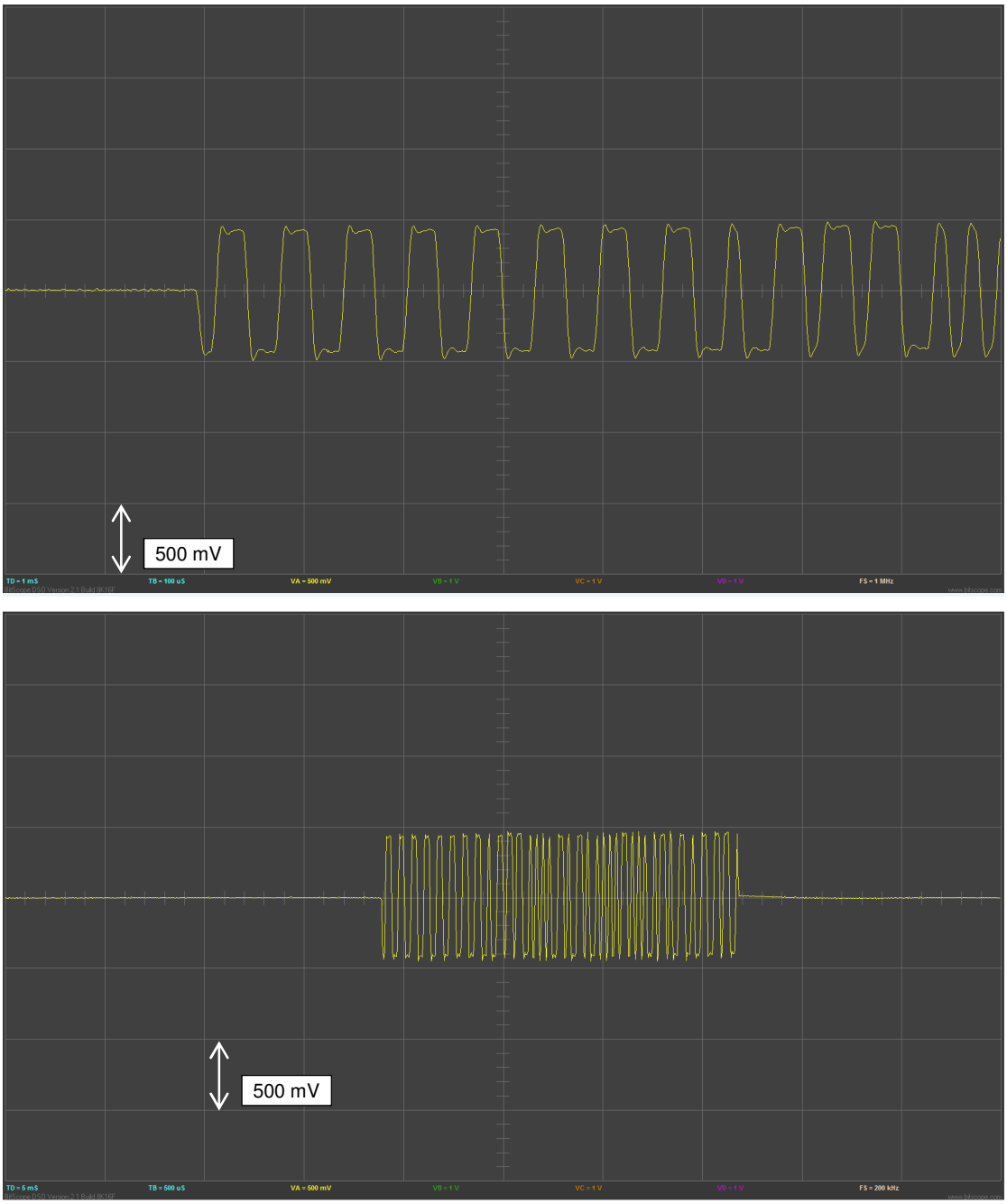


Figure 4.5 Normal Operation FF Signal Traces.

During a normal operation the CiF was operating and controlling as expected. Three data-links were updated every 500ms scheduled by the LAS. This is indicated by the green color of the data values on the following screenshot (Figure 4.6) during the strategy monitoring.

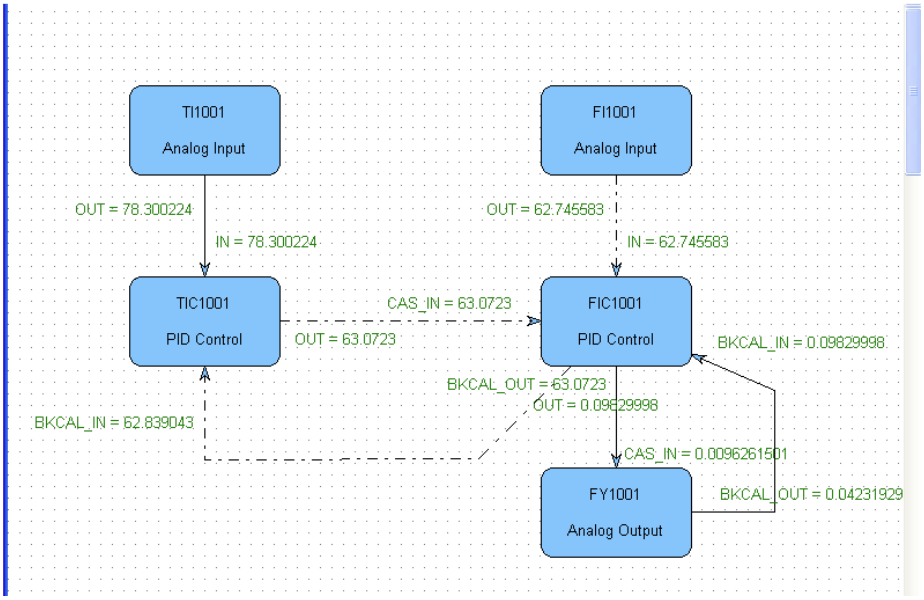


Figure 4.6 CiF Control Module in Healthy (Normal) State.

This was also verified by analyzing the FF message packets captured by the FB Logger. When it was time for a link to be published, the LAS sends a Compel Data 2 or CD2 to request the device that produces this output to send it immediately [17] to the bus. This is identified by the highlighted packets in Figure 4.7, and the destination of this CD2 message is 1A (hex), which is exactly what TT1001 had as address. Therefore, the packet 267 was from the LAS to the

Number	Time	Frame
262	-00:00:00.038	DT1 dest: 1927 src : 10A9
263	-00:00:00.033	RT
264	-00:00:00.026	IDLE
265	-00:00:00.021	IDLE
266	-00:00:00.015	IDLE
267	00:00:00.000	CD2 dest: 1A20
268	00:00:00.009	DT3 src : 1A20 InvID: FF Information Report Idx: 909 Data: C2 42 C8 00 00
269	00:00:00.015	IDLE
270	00:00:00.030	CD2 dest: 1820
271	00:00:00.042	DT3 src : 1820 InvID: FF Information Report Idx: 708 Data: 80 42 04 CE AF
272	00:00:00.060	CD2 dest: 1920
273	00:00:00.072	DT3 src : 1920 InvID: FF Information Report Idx: 931 Data: C2 42 C8 00 00
274	00:00:00.079	PT dest: 11
275	00:00:00.085	RT
276	00:00:00.092	PT dest: 18

Figure 4.7 FF Packets of the Publishing Data Links.

TT1001 to publish its link data. The TT1001 responds by sending the data encapsulating it in a DT2 packet, which is the next packet #268. Similarly, the LAS compels data link publication from FT1001 with address 18h (packet #270) and FV1001 with address 19h (packet #272), and the devices obliges at frame #271 and #273 respectively. This process repeats every 500ms deterministically until a fault prevents the devices from receiving message from each other. The time 500ms was programmed during the configuration of the control strategy as the Macrocycle of the test segment. During a cable fault there would be interruptions/faults of this data link publication in the captured packets. The alternative *path recovery time* [18] must be less than 500ms for the loop to work uninterrupted. Refer to Appendix A for the complete set of packets captured for the full 500ms Macrocycle schedule. Next, a cable break was induced to establish fault-state behavior.

4.3 Cable Fault

The switches S4 and S5 are toggled open to break open the H1 segment while everything else kept unchanged. The very first observation was that the control strategy did not show any good data at FV1001 from the TT1001. The PID control block held the last value in red color to indicate such fault. This is shown on Figure 4.8 (CAS_IN). The FF signal was recorded by

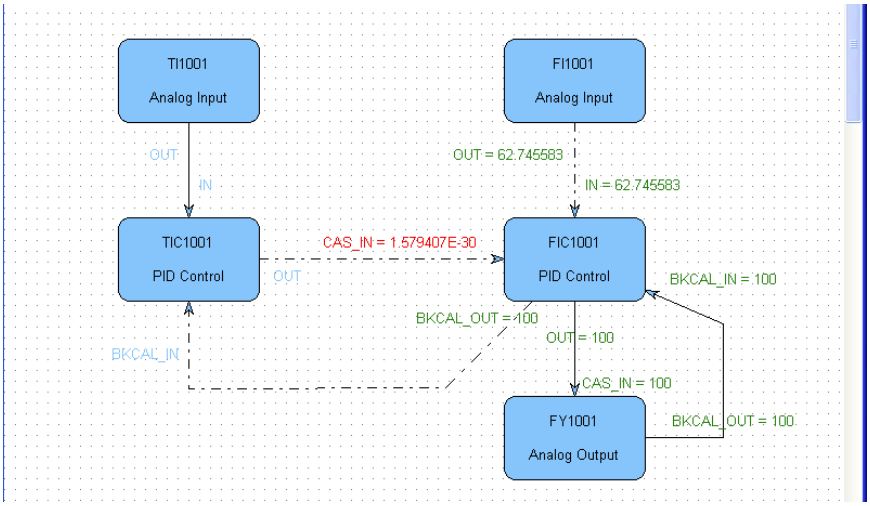


Figure 4.8 CiF Control Module in Healthy (Normal) State.

oscilloscope from both sides of the broken segment, and the signals from both fractions of the network revealed increased peak-to-peak amplitude. The signal was closer to 1.4 to 1.5 volts which does not conform to the specification, but consistent with segment with a missing terminator [5]. Figure 4.9 shows the signal samples from the network part belong to LDP (top) and LDB (bottom) after the segment break was induced.

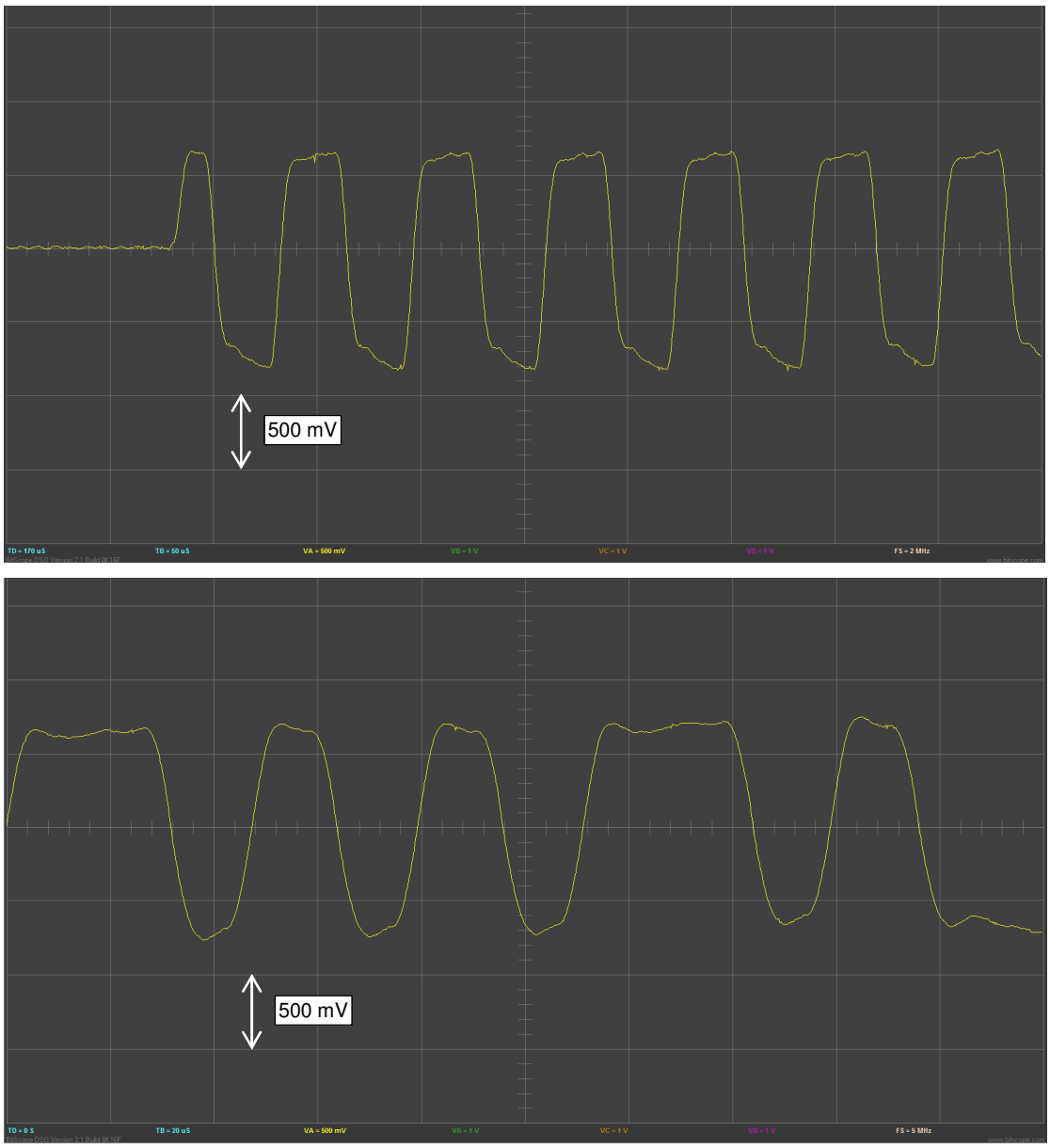


Figure 4.9 FF Signal Amplitude Increased During Cable Break (without DSR).

The data packets were collected as well from both sides of the broken segment. The data link packets belonging to the primary LD (LDP) was reviewed first (Figure 4.10). Clearly, one of the data links was no longer being published on this segment. There was a *compel* data (CD2) request from the LAS to TT1001, but since the TT1001 was separated out into the other part of the segment, it never reached its destination (or the response from the TT1001 never arrives into this segment).

Number	Time	Frame
11	-00:00:00.071	RT
12	-00:00:00.065	PT dest: 18
13	-00:00:00.057	RT
14	-00:00:00.049	PN dest: F3
15	-00:00:00.023	IDLE
16	-00:00:00.017	IDLE
17	00:00:00.000	CD2 dest: 1A20
18	00:00:00.030	CD2 dest: 1820
19	00:00:00.042	DT3 src : 1820 InvID: FF Information Report Idx: 708 Data: 80 42 7A FB 7A
20	00:00:00.060	CD2 dest: 1920
21	00:00:00.072	DT3 src : 1920 InvID: FF Information Report Idx: 931 Data: CE 42 C8 00 00
22	00:00:00.079	PT dest: 19
23	00:00:00.087	RT
24	00:00:00.093	PT dest: 10
25	00:00:00.099	RT
26	00:00:00.105	PT dest: 10

Figure 4.10 Packets from Segment with LDP without DSR Active.

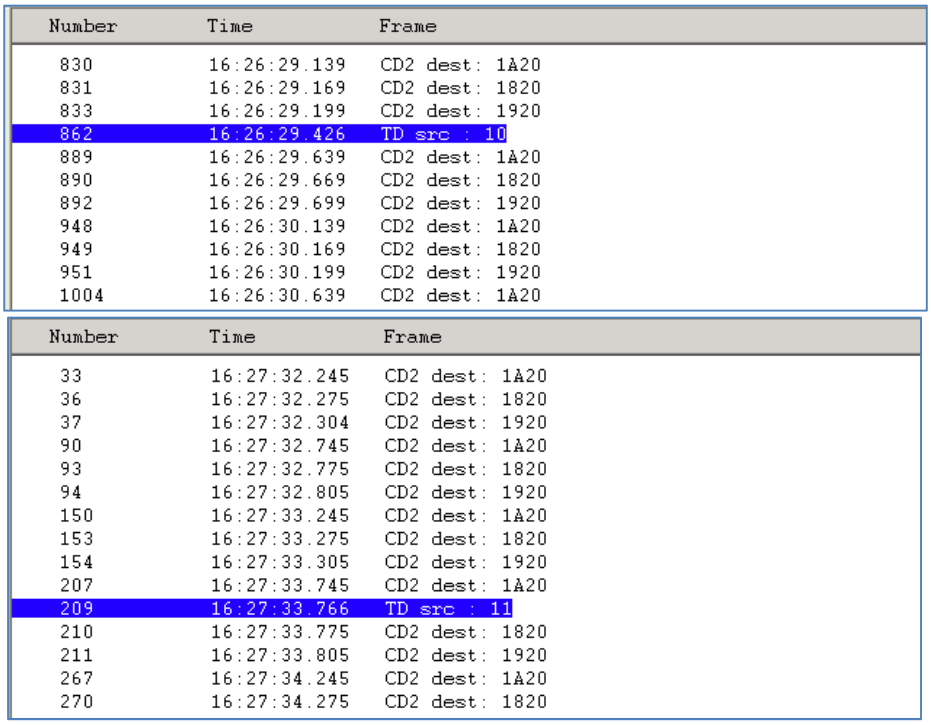
On the other hand, the packets from segment belonging to the backup LD (LDB) showed that only link was being published was the data link from the TT1001 while CD2 request to FT1001 and FV1001 were going unanswered (Figure 4.11).

Number	Time	Frame
28	-00:00:00.042	IDLE
29	-00:00:00.037	IDLE
30	-00:00:00.031	IDLE
31	-00:00:00.026	IDLE
32	-00:00:00.020	IDLE
33	00:00:00.000	CD2 dest: 1A20
34	00:00:00.009	DT3 src : 1A20 InvID: FF Information Report Idx: 909 Data: C2 42 C8 00 00
35	00:00:00.015	IDLE
36	00:00:00.030	CD2 dest: 1820
37	00:00:00.059	CD2 dest: 1920
38	00:00:00.085	PN dest: F8
39	00:00:00.113	PT dest: 11
40	00:00:00.118	RT
41	00:00:00.125	PT dest: 11
42	00:00:00.130	RT

Figure 4.11 Packets from Segment with LDB without DSR Active.

Obviously, each new network segment had an active LAS to issue compel data command (CD2) into that network. They reveal themselves when packets were filtered to determine the LAS addresses of the time distribution source addresses. Figure 4.12 confirms this finding

(network with the LDP on top and network with the LDB at bottom). This was the exact condition proposed DSR framework supposed to detect with its fault detection algorithm (Figure 3.4) before initiating corrective actions. Up next, the network was restored by activating the DSR apparatus. Initially, it would be a delayed restore since data had been collected and examined from each network parts in detail during the fault state. Later a quick (immediate) restore was exercised and evaluated as it to mimic a proper embedded DSR behavior.



Number	Time	Frame
830	16:26:29.139	CD2 dest: 1A20
831	16:26:29.169	CD2 dest: 1820
833	16:26:29.199	CD2 dest: 1920
862	16:26:29.426	TD src : 10
889	16:26:29.639	CD2 dest: 1A20
890	16:26:29.669	CD2 dest: 1820
892	16:26:29.699	CD2 dest: 1920
948	16:26:30.139	CD2 dest: 1A20
949	16:26:30.169	CD2 dest: 1820
951	16:26:30.199	CD2 dest: 1920
1004	16:26:30.639	CD2 dest: 1A20

Number	Time	Frame
33	16:27:32.245	CD2 dest: 1A20
36	16:27:32.275	CD2 dest: 1820
37	16:27:32.304	CD2 dest: 1920
90	16:27:32.745	CD2 dest: 1A20
93	16:27:32.775	CD2 dest: 1820
94	16:27:32.805	CD2 dest: 1920
150	16:27:33.245	CD2 dest: 1A20
153	16:27:33.275	CD2 dest: 1820
154	16:27:33.305	CD2 dest: 1920
207	16:27:33.745	CD2 dest: 1A20
209	16:27:33.766	TD src : 11
210	16:27:33.775	CD2 dest: 1820
211	16:27:33.805	CD2 dest: 1920
267	16:27:34.245	CD2 dest: 1A20
270	16:27:34.275	CD2 dest: 1820

Figure 4.12 LDP and LDB Both Become Active LAS.

4.4 Fault Recovery

Delayed Restore

The switches S1, S2 and S3 are turned on simultaneously to activate the DSR restoration. A 3PDT type switch was used so that all three switches may be toggled simultaneously. Instantly, the FF signal level on the network was observed to be restored to steady-state level (Figure 4.13).

While segment was at fault, the FIC1001 controller's MODE had shed to AUTO instead of running in CASCADE (CAS) since it could not receive any more good data on its CAS_IN pin from the TIC1001. The FIC1001 was configured intentionally to shed to AUTO mode at bad communication, and to stay there until the operator changes it back to CAS. This little configuration bit was utilized to determine if the segment recovered quickly enough when it gets restored instantly (rather than delayed) during the quick restore performance is evaluated. If the segment recovers timely, i.e., no *loss of control*, the mode of the FIC1001 would stay in CAS (both TARGET and ACTUAL), but if it takes too long to recover, the FIC1001 controller's mode would be found in AUTO instead of CAS implying a *loss of control*. Figure 4.14 shows detail configuration of the FIC1001 function block for this setting.

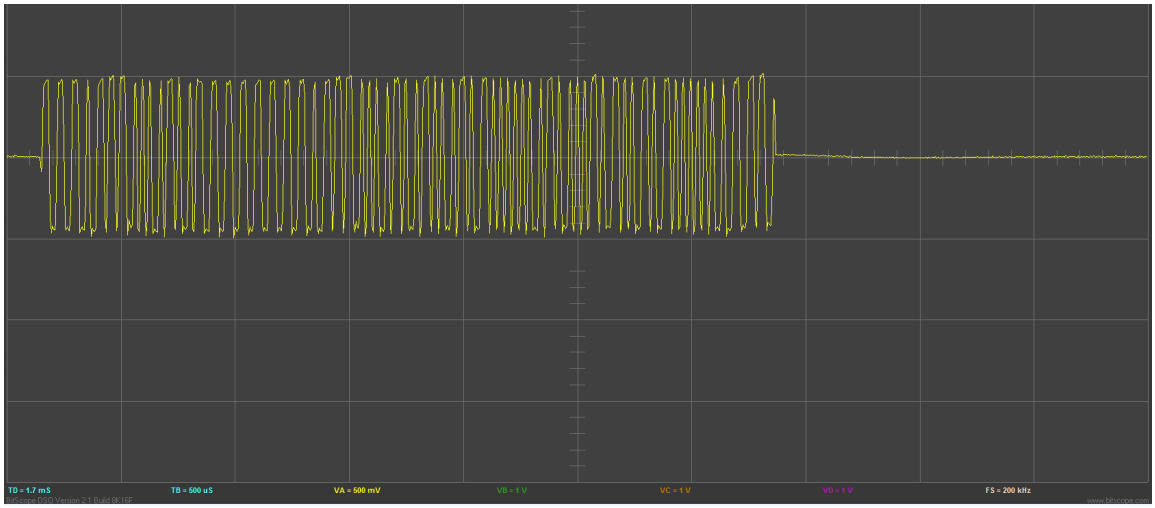


Figure 4.13 Restored FF Signal Within Valid Voltage Range.

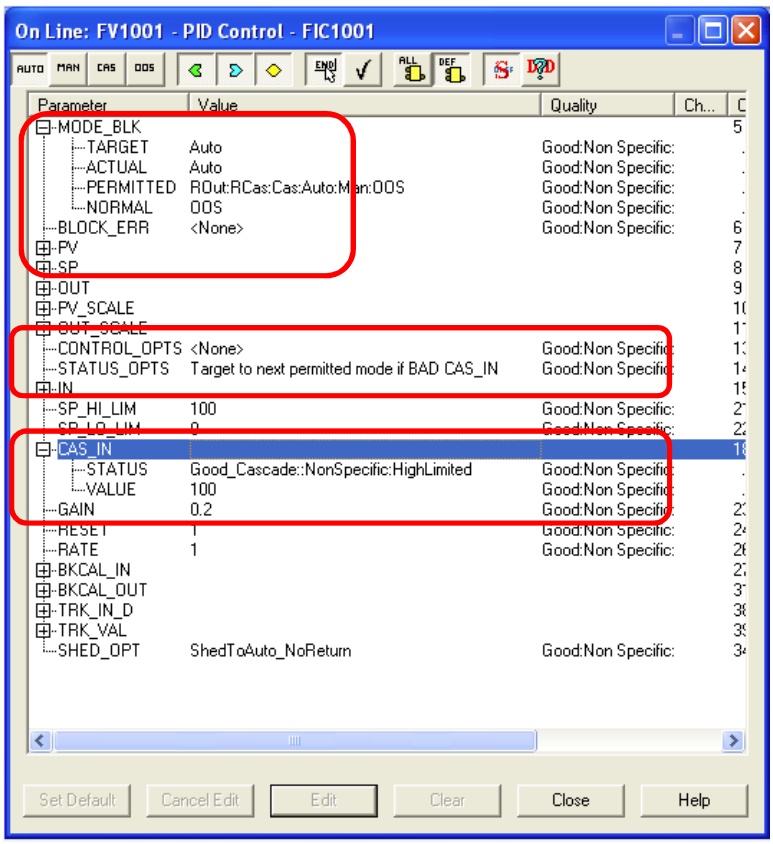


Figure 4.14 Data Link Restored but MODE Shed to AUTO for Delayed Restore.

Analyzing the message packets from the FF data logger confirmed that all links were restored and one LAS dropped out to become backup LAS (Figure 4.15).

Number	Time	Frame
14290	16:33:17.755	RT
14291	16:33:17.762	PT dest: 11
14292	16:33:17.768	RT
14293	16:33:17.773	IDLE
14294	16:33:17.779	IDLE
14295	16:33:17.785	IDLE
14296	16:33:17.791	IDLE
14297	16:33:17.807	CD2 dest: 1A20
14298	16:33:17.820	DT3 src : 1A20 InvID: FF Information Report Idx: 909 Data: C2 42 C8 00 00
14299	16:33:17.836	CD2 dest: 1820
14300	16:33:17.849	DT3 src : 1820 InvID: FF Information Report Idx: 708 Data: 80 42 7A FB 7A
14301	16:33:17.866	CD2 dest: 1920
14302	16:33:17.879	DT3 src : 1920 InvID: FF Information Report Idx: 931 Data: CE 42 C8 00 00
14303	16:33:17.886	PT dest: 10
14304	16:33:17.892	RT

Figure 4.15 All Three Links are Restored (DSR Active).

Instant Restore

Before running the instant/quick restore test, the FIC1001 was set back into CAS mode so that it can be inspected after the restore for signs of failure or success. All switches were set back to their original position, and the segment was running as it had been before the induced

cable break. Once the system is at the steady state, the switches S4/S5 followed immediately (roughly within 500 ms) by S1/2/3 are toggled. By doing so a cable fault was induced and within (less than) half a second the DSR apparatus was activated to counter the fault. During the process, the data packets and signal traces were captured. The control module was monitored from the supervisory station while data was trending on a chart view. Control module seemed to be always in good communication with all of its function blocks, and the FF data packets also revealed no interruption of publishing any of the data links. The final check was to verify if the FIC1001 controller had shed to AUTO mode. Inspection revealed no such mode shedding, it was found to be operating in CAS mode. Figure 4.16 shows the data trending of the control module including the FIC1001's MODE. It was evident that the Master (TIC1001) and Slave (FIC1001) controllers were always in good communication as small PV (process variable) changes in the TIC1001 cascaded action into the FIC1001. All the while the MODE for FIC1001 was in CAS (enumerated 4) indicating an uninterrupted control operation.

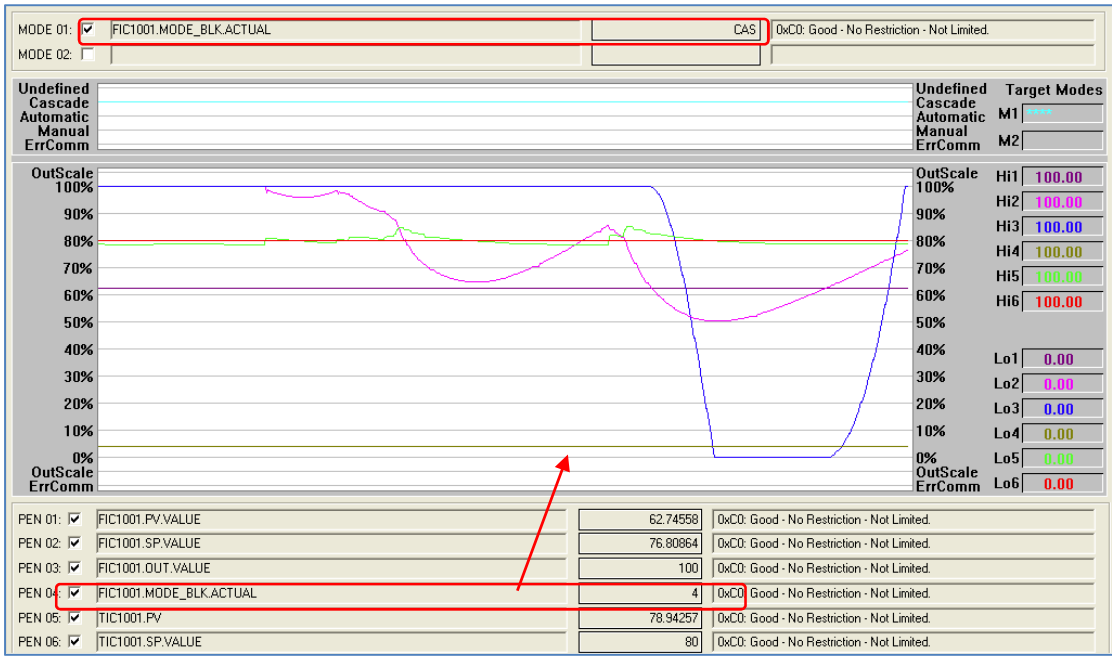


Figure 4.16 Supervisory Data Trending During Cable Fault (with DSR Activated).

Summary

This chapter described the prototyping of a functionally equivalent Dynamic Synchronization Repeater, and a test H1 segment using topology framework outlined in this thesis. A real-world cascaded loop was implemented using the CiF technology where function blocks were distributed among three devices on the segment. The objective was to demonstrate the efficacy of proposed solution in terms of maintaining uninterrupted control and communication on the test segment with a broken trunk. A cable break was induced while control loops were monitored and recorded. Steady-state readings of the segment were recorded prior to the fault introduction so that, a baseline for a normal operation could be established. The data collected prior, during, and after the fault were compared to validate communication and control. Lastly, a control shedding flag was set in the secondary controller of the control application (CiF) so that, it would shed to a lower mode (CAS to AUTO) if for any reason it failed to receive good data from the primary controller. The secondary controller was found to be in the CAS mode even after the cable fault was introduced. In other words, there was no *loss of control* or communication with the DSR engaged.

5. Conclusion

The Foundation Fieldbus is an all-digital control system infrastructure offering unprecedented level of flexibility and scalability for modern process control system. Nevertheless, reaping all these benefits has been slow due to various challenges to this technology. While challenges of designing, commissioning, and maintaining the FF control systems have been handled with industry established engineering and maintenance best practices, the lack of physical layer (media) redundancy of the H1 network has been an open issue that impacts the confidence of the end-user directly when it comes to use of the Control in Field (CiF). In this thesis a framework for media redundancy of the H1 network was proposed using the Dynamic Synchronization Repeater (DSR). A functionally equivalent prototype was constructed to evaluate the proposed solution on a fully redundant test segment (H1) operating a cascaded CiF loop. The effectiveness of the solution was verified with real-time monitoring of the control loop as well the FF signals and messages on the test segment.

Impact of having a redundant H1 network could be far reaching as it would encourage more CiF implementation by taking away the risk of the segment break. The CiF is one of the premium capabilities of the FF technology that impacts its capacity to influence the availability of the system by achieving the single loop integrity. Besides, overall availability of a control system is directly influenced by the availability of its communication network, thus media redundancy on the H1 segment surely would make the control systems more available [19] [20]. It also influences the scalability of a system. When the CiF are the norm of *simple* and *cascade* control loops deployment, adding additional FF instrument in the system means adding more control capabilities. This also frees up the central controllers' resources to be dedicated for complex control operations.

The focus of this thesis has been to propose a solution that has the minimum impact in terms of new component requirement and the complexity of the solution. Care has been also

given so that any working solution does not take away the capacity of the H1 network in terms of available cable length (1900m). Instead of adopting traditional LAN based fault-tolerant approach as they could become very complex to implement [21], off-the-shelf component (H1 Active Repeater) was repurposed to develop the Dynamic Synchronization Repeater (DSR) that turns one broken part of the segment into an extension of the original segment at cable-break detection, and by doing so it maintains the original segment functionalities uninterrupted with minimum programming requirements. The DSR was also envisioned to generate fault alert when it was engaged to correct cable fault. The active repeaters typically counted as one FF device on the H1 segment, as a result the H1 segments designed to use this DSR framework for media redundancy must count the DSR as one device toward its total instrument counts. In other words, H1 segments with DSR topology may have up to 15 (not 16) bus-powered instruments per network.

The Profibus PA protocol is another industrial network protocol that uses the same Physical Layer specification (IEC61158) as the Foundation Fieldbus H1; therefore, the solution proposed in this thesis may as well be adopted to apply for the Profibus PA networks. The fault detection mechanism would be different from what was described here for the FF, but the same Dynamic Synchronization Repeaters could be used to construct a solution.

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APPENDIX

A. **FF Message Packets of Healthy Steady-State Segment Covering Full Macrocycle**.

Number	Time	Frame
263	-00:00:00.033	RT
264	-00:00:00.026	IDLE
265	-00:00:00.021	IDLE
266	-00:00:00.015	IDLE
267	00:00.000	CD2 dest: 1A20
268	00:00.009	DT3 src : 1A20 InvID: FF Information Report Idx: 909 Data: C2 42 C8 00 00
269	00:00.015	IDLE
270	00:00.030	CD2 dest: 1820
271	00:00.042	DT3 src : 1820 InvID: FF Information Report Idx: 708 Data: 80 42 04 CE AF
272	00:00.060	CD2 dest: 1920
273	00:00.072	DT3 src : 1920 InvID: FF Information Report Idx: 931 Data: C2 42 C8 00 00
274	00:00.079	PT dest: 11
275	00:00.085	RT
276	00:00.092	PT dest: 18
277	00:00.100	RT
278	00:00.107	PT dest: 19
279	00:00.114	RT
280	00:00.121	PT dest: 1A
281	00:00.129	RT
282	00:00.135	PT dest: 10

Number	Time	Frame
283	00:00.144	DT1 dest: 1927 src : 10A9 InvID: 63 Read Req Idx: 2494
284	00:00.151	DT1 dest: 18F7 src : 10AA
285	00:00.157	RT
286	00:00.163	PT dest: 10
287	00:00.168	RT
288	00:00.175	PT dest: 11
289	00:00.181	RT
290	00:00.187	PT dest: 18
291	00:00.195	RT
292	00:00.202	PT dest: 19
293	00:00.224	DT1 dest: 10A9 src : 1927 InvID: 63 Read Pos Resp Len: 43 Data: 00 15 30 20 F9 01 00 00 80 42 04 CE AF C2 42 C8 00 00 C2 42 C8 00 00 C2 42 C8 00 00 1C 00 1C 00 00 00 00 00 00 00 00 00 00 00 00
294	00:00.232	PN dest: FC
295	00:00.259	PT dest: 1A
296	00:00.267	RT
297	00:00.274	PT dest: 10
298	00:00.280	DT1 dest: 1927 src : 10A9
299	00:00.289	DT1 dest: 1927 src : 10A9 InvID: 64 Read Req Idx: 2496
300	00:00.295	RT
301	00:00.301	PT dest: 11
302	00:00.307	RT
303	00:00.314	PT dest: 18

Number	Time	Frame
304	00:00.322	RT
305	00:00.329	PT dest: 19
306	00:00.337	RT
307	00:00.343	PT dest: 1A
308	00:00.351	RT
309	00:00.358	PT dest: 10
310	00:00.363	RT
311	00:00.370	PT dest: 11
312	00:00.375	RT
313	00:00.382	PT dest: 18
314	00:00.390	RT
315	00:00.397	PT dest: 19
316	00:00.406	DT1 dest: 10A9 src : 1927
317	00:00.413	PT dest: 1A
318	00:00.421	RT
319	00:00.427	PT dest: 1A
320	00:00.437	RT
321	00:00.443	PT dest: 10
322	00:00.449	RT
323	00:00.455	PT dest: 11
324	00:00.461	RT
325	00:00.467	IDLE
326	00:00.473	IDLE
327	00:00.478	IDLE

Number	Time	Frame
328	00:00.483	IDLE
329	00:00.500	CD2 dest: 1A20
330	00:01.000	DT3 src : 1A20 InvID: FF Information Report Idx: 909 Data: C2 42 C8 00 00
331	00:00.515	IDLE
332	00:00.531	CD2 dest: 1820
333	00:00.542	DT3 src : 1820 InvID: FF Information Report Idx: 708 Data: 80 42 04 CE AF
334	00:00.560	CD2 dest: 1920
335	00:00.572	DT3 src : 1920 InvID: FF Information Report Idx: 931 Data: C2 42 C8 00 00
336	00:00.579	PT dest: 18

B. FF Message Packets on Broken Segment (LDP).

Number	Time	Frame
85	00:00.461	IDLE
86	00:00.466	IDLE
87	00:00.472	IDLE
88	00:00.478	IDLE
89	00:00.483	IDLE
90	00:00.500	CD2 dest: 1A20
91	00:00.509	DT3 src : 1A20 InvID: FF Information Report Idx: 909 Data: C2 42 C8 00 00
92	00:00.515	IDLE
93	00:00.530	CD2 dest: 1820
94	00:00.560	CD2 dest: 1920
95	00:00.585	PT dest: 11
96	00:00.590	RT
97	00:00.596	PT dest: 1A
98	00:00.604	RT
99	00:00.611	PT dest: 11
100	00:00.616	RT
101	00:00.622	PT dest: 1A
102	00:00.630	RT
103	00:00.637	PT dest: 11
104	00:00.643	RT
105	00:00.650	PN dest: F0
106	00:00.677	PT dest: 1A

Number	Time	Frame
107	00:00.685	RT
108	00:00.692	PT dest: 11
109	00:00.697	RT
110	00:00.703	PT dest: 1A
111	00:00.711	RT
112	00:00.718	PT dest: 11
113	00:00.723	RT
114	00:00.730	PT dest: 1A
115	00:00.737	RT
116	00:00.744	PT dest: 11
117	00:00.749	RT
118	00:00.756	PT dest: 1A
119	00:00.764	RT
120	00:00.770	PT dest: 11
121	00:00.776	RT
122	00:00.782	PT dest: 1A
123	00:00.790	RT
124	00:00.797	PT dest: 11
125	00:00.802	RT
126	00:00.808	PT dest: 1A
127	00:00.816	RT
128	00:00.824	PN dest: FA
129	00:00.851	PT dest: 11
130	00:00.857	RT

Number	Time	Frame
131	00:00.863	PT dest: 1A
132	00:00.871	RT
133	00:00.877	PT dest: 11
134	00:00.883	RT
135	00:00.889	PT dest: 1A
136	00:00.897	RT
137	00:00.904	PT dest: 11
138	00:00.909	RT
139	00:00.916	PT dest: 1A
140	00:00.923	RT
141	00:00.930	PT dest: 11
142	00:00.936	RT
143	00:00.943	PT dest: 11
144	00:00.948	RT
145	00:00.954	PT dest: 1A
146	00:00.962	RT
147	00:00.968	IDLE
148	00:00.974	IDLE
149	00:00.980	IDLE
150	00:01.000	CD2 dest: 1A20
151	00:01.009	DT3 src : 1A20 InvID: FF Information Report Idx: 909 Data: C2 42 C8 00 00
152	00:01.015	IDLE
153	00:01.030	CD2 dest: 1820

Number	Time	Frame
154	00:01.060	CD2 dest: 1920
155	00:01.085	PN dest: F1
156	00:01.113	PT dest: 11
157	00:01.118	RT
158	00:01.125	PT dest: 11
159	00:01.130	RT
160	00:01.137	PT dest: 1A
161	00:01.144	RT
162	00:01.151	PT dest: 11
163	00:01.157	RT
164	00:01.163	PT dest: 1A
165	00:01.171	RT
166	00:01.178	PT dest: 11
167	00:01.183	RT
168	00:01.190	PT dest: 1A
169	00:01.197	RT
170	00:01.204	PT dest: 11
171	00:01.209	RT
172	00:01.216	PT dest: 1A
173	00:01.224	RT
174	00:01.231	PT dest: 11
175	00:01.236	RT
176	00:01.242	PT dest: 1A
177	00:01.250	RT

C. FF Message Packets on Broken Segment (LDB).

Number	Time	Frame
1	-00:00:00.139	RT
2	-00:00:00.133	PT dest: 10
3	-00:00:00.127	RT
4	-00:00:00.121	PT dest: 18
5	-00:00:00.113	RT
6	-00:00:00.106	PT dest: 19
7	-00:00:00.099	RT
8	-00:00:00.091	PT dest: 19
9	-00:00:00.084	RT
10	-00:00:00.077	PT dest: 10
11	-00:00:00.071	RT
12	-00:00:00.065	PT dest: 18
13	-00:00:00.057	RT
14	-00:00:00.049	PN dest: F3
15	-00:00:00.023	IDLE
16	-00:00:00.017	IDLE
17	00:00.000	CD2 dest: 1A20
18	00:00.030	CD2 dest: 1820
19	00:00.042	DT3 src : 1820 InvID: FF Information Report Idx: 708 Data: 80 42 7A FB 7A
20	00:00.060	CD2 dest: 1920
21	00:00.072	DT3 src : 1920 InvID: FF Information Report Idx: 931 Data: CE 42 C8 00 00

Number	Time	Frame
22	00:00.079	PT dest: 19
23	00:00.087	RT
24	00:00.093	PT dest: 10
25	00:00.099	RT
26	00:00.105	PT dest: 10
27	00:00.111	RT
28	00:00.117	PT dest: 18
29	00:00.125	RT
30	00:00.131	PT dest: 19
31	00:00.139	RT
32	00:00.146	PT dest: 10
33	00:00.151	RT
34	00:00.158	PT dest: 18
35	00:00.165	RT
36	00:00.172	PT dest: 19
37	00:00.180	RT
38	00:00.187	PT dest: 10
39	00:00.192	RT
40	00:00.200	PN dest: FE
41	00:00.227	PT dest: 18
42	00:00.235	RT
43	00:00.241	PT dest: 19
44	00:00.249	RT
45	00:00.256	PT dest: 10

Number	Time	Frame
46	00:00.261	RT
47	00:00.267	PT dest: 18
48	00:00.275	RT
49	00:00.282	PT dest: 19
50	00:00.290	RT
51	00:00.297	PT dest: 10
52	00:00.302	RT
53	00:00.309	PT dest: 18
54	00:00.316	RT
55	00:00.323	PT dest: 19
56	00:00.331	RT
57	00:00.338	PT dest: 10
58	00:00.343	RT
59	00:00.349	PT dest: 18
60	00:00.357	RT
61	00:00.364	PT dest: 19
62	00:00.372	RT
63	00:00.380	PN dest: F4
64	00:00.407	PT dest: 10
65	00:00.413	RT
66	00:00.419	PT dest: 18
67	00:00.427	RT
68	00:00.434	PT dest: 19
69	00:00.442	RT

Number	Time	Frame
70	00:00.449	PT dest: 10
71	00:00.454	RT
72	00:00.460	IDLE
73	00:00.466	IDLE
74	00:00.471	IDLE
75	00:00.477	IDLE
76	00:00.483	IDLE
77	00:00.500	CD2 dest: 1A20
78	00:00.530	CD2 dest: 1820
79	00:00.542	DT3 src : 1820 InvID: FF Information Report Idx: 708 Data: 80 42 7A FB 7A
80	00:00.560	CD2 dest: 1920
81	00:00.572	DT3 src : 1920 InvID: FF Information Report Idx: 931 Data: CE 42 C8 00 00
82	00:00.579	PT dest: 10
83	00:00.584	RT
84	00:00.591	PT dest: 18
85	00:00.599	RT
86	00:00.606	PN dest: FF
87	00:00.633	PT dest: 19
88	00:00.641	RT
89	00:00.648	PT dest: 10
90	00:00.653	RT