Contents

	Page
List of Tables.	**x**
List of Figures.	**xi**
List of Symbols.	**xv**
Dedication.	**xxi**
Acknowledgment.	**xxi**
Abstract.	**xxii**
Chapter 1 Introduction to FieldBuses Systems.	**1**
1.1. The Definition of a Fieldbus.	1
1.1.1. Why Define a Bus?	3
1.2. An Introduction to Industrial Systems Communications.	5
1.2.1. Process industry: a Historical background.	5
1.2.2. Manufacturing industry: a Historical background	9
1.3. The Fieldbuses and the Network Reference Model.	14
1.4. Different Types of Fieldbuses.	17
1.5. CERN Recommendations on FieldBuses.	20
1.5.1. Controller Area Network.	21
1.5.2. Process Field Bus.	22

1.5.3. World Factory Instrumentation Protocol. 22

1.6. Comparison between different types of FieldBuses. 24

1.7. The Future of the Fieldbus Systems. 27

Chapter 2
The FIP Protocol Standard and Specifications. 29

2.1. Brief history of Factory Instrumentation Protocol. 29

2.2. The Definition of FIP Protocol. 30

2.3. The Overall Configuration of WorldFIP. 31

2.4. The WorldFIP Physical Layer. 32

2.5. The WorldFIP Data Link Layer (DLL). 33

2.5.1. The Data Link Layer Services. 33

2.5.2. Addressing of Variables and Messages. 34

2.5.2.1. Variable Addressing. 34

2.5.2.2. Message Addressing. 34

2.5.4. The FIP Network Configuration. 36

2.5.5. The Bus Arbitrating Tables. 36

2.5.6. Using HCF/ LCM Methodology for Setting the BAT 38

2.5.7. The BA Periodic Variables Scanning Mechanism. 40

2.5.8. Numerical Example of BAT. 40

2.5.9. Modes of Operation of the WorldFIP. 42

2.5.10. Medium Allocation mechanism for Aperiodic variables. 43

2.5.11. Medium Allocation of the Aperiodic Messages. 47

2.5.11.1. Unack. Message transfer request. 47

2.5.11.2. Acknowledged Message transfer request. 50

2.6. The WorldFIP Application Layer. 52

2.6.1. Refreshment. 52

2.6.1.1. Asynchronous Refreshment. 52

2.6.1.2. Synchronous Refreshment. 54

2.6.2. Promptness. 55

2.6.2.1. Asynchronous Promptness. 55

Chapter 3
Real-Time Communications in WorldFIP 57

3.1. Introduction to FIP Real-Time Analyses. 57

3.2. Changing the Scheduling Method Statically. 58

3.2.1. The Memory-Reduction Scheduling Method. 58

3.2.2. The Jitter-Resolving Scheduling Method. 60

3.3. Changing the Scheduling Method Dynamically. 63

3.4. Calculating the WCRT of FIP Sporadic Streams. 66

3.5. The Stability of FIP Control Loops. 70

3.5.1. Effect of Network Delay on the Control Loop Stability. 70

3.5.2. Determination of Sampling Periods of The Control Loops. 75

3.6. WorldFIP Clock Synchronization. 78

3.6.1. Why the Clock Synchronization? 78

3.6.2. Clock Synchronization from the Application Layer. 78

3.7. Deriving Task Attributes. 79

Chapter 4
Calculating the Worst Case Response Time of the FIP. 82

4.1. Sequence of Aperiodic Traffic in FIP Network. 83

4.2. Model Assumptions and Parameters. 86

4.3. Calculating the Worst Case Response Time of the Urgent Aperiodic Traffic. 89

4.3.1. Numerical Example 1. 91

4.3.2. The WorldFIP Traffic Simulation Results 94

4.4. The WCRT of the Normal Aperiodic Variables. 101

4.4.1. Extended Model Parameters 102

4.4.2. Calculating the WCRT of Normal Aperiodic Variables. 103

4.4.2.1. Calculating $NABI_N$. 104

4.5.1. Notes on the WCRT of the Normal Aperiodic Variables. 106

Chapter 5
A Modified Scheduling Algorithm for FIP Fieldbus Systems. 107

5.1. What are the Advantages we gain from this Algorithm? 108

5.1.2. The differences between our algorithm and the one proposed by [Hong 95]. 109

5.2. Identification of the FIP system model. 109

5.3. The Model of Feedback Control System with Variable Time Delay 114

5.3.1. Modified Loop Delay. 115

5.4. The Modified Window Scheduling Algorithm To Determine The Data Sampling Times of the FIP ICCS. 117

5.4.1. The Model Parameters. 117

5.4.2. The determination of the smallest sampling time. 118

5.5. The Construction of FIP Bus Arbitrator Table using the Modified Algorithm. 122

5.6. The Periodic Variables Network Utilization. 123

5.6.1. The First Mathematical Representation. 123

5.6.2. The Second Mathematical Representation. 124

5.6.3. Numerical Example 1. 124

5.7. A Further Modification to the Scheduling Algorithm. 126

5.7.1. Summary of the modified algorithm. 128

5.7.2. Numerical Example 2. 128

5.8. Matlab Simulation. 130

5.9. Conclusion. 132

Chapter 6
Summary, Conclusion, and Future work. **133**

Chapter 7
References. **140**

List of Tables

		Page
Table 1.1.	Comparison between Different types of Fieldbuses	**24-25**
Table 2.1.	The BAT Example.	**40**
Table 4.1.	Numerical Example E.4.1.	**92**
Table 4.2.	The theoretical Values of the Urgent Aperiodic Variable .WCRT	**93**
Table 4.3.	The Simulation Results of Phase one.	**98**

List of Figures

		Page
Fig. 1.1.	Star topology typically used in the architecture of Process Control Systems up to the 1960s.	**6**
Fig. 1.2.	The hierarchical architecture which was popular in Process Control Systems during the early 1970s.	7
Fig. 1.3.	A first approach towards a distributed architecture introduced in Process Control Systems after the mid 1970s.	8
Fig. 1.4.	The fully distributed architecture, based on a fieldbus, found in modern industrial automation systems.	9
Fig. 1.5.	The trend towards the use of a distributed architecture in manufacturing industry to interconnect cells across the plant.	11
Fig. 1.6.	The Computer Integrated Manufacturing (CIM) Architecture.	**11**
Fig. 1.7.	Comparison between the point-to-point and the fieldbus Hierarchies.	**14**
Fig. 1.8.	The OSI 7-layers reference model (a), and the reduced fieldbus 3-layer structure (b).	**16**
Fig. 1.9.	FlexRay Active Star Topology.	**27**
Fig.2.1.	The WorldFIP Layered Architecture.	**31**
Fig.2.2.	Example of the Physical Connections in FIP System.	**32**
Fig.2.3.	The ID_DAT frame, the RP_DAT frame, and the RP_MSG frame.	**35**
Fig.2.4.	WorldFIP Network Configuration.	**36**
Fig.2.5.	WorldFIP Network Traffic Load.	**41**

Fig.2.6.	WorldFIP Elementary Cycle Windows.	**42**
Fig.2.7.	Stage one of Aperiodic Variable Transaction.	**44**
Fig.2.8.	Stage two of Aperiodic Variable Transaction.	**45**
Fig.2.9.	Stage Three of Aperiodic Variable Transaction.	**46**
Fig.2.10.	First Stage of Unacknowledged Message Transaction.	**48**
Fig.2.11.	Second Stage of Unacknowledged Message Transaction.	**49**
Fig.2.12.	Third Stage of Unacknowledged Message transaction.	**50**
Fig.2.13.	Acknowledge Packet from Sender.	**50**
Fig.2.14.	RP_ACK Frame sent by BA.	**51**
Fig.2.15.	Asynchronous Refreshment Mechanism.	**53**
Fig.2.16.	Timing Diagram of the Asynchronous Refreshment Example.	**53**
Fig.2.17.	Timing Diagram of a Synchronous Refreshment Example.	**54**
Fig.2.18.	Asynchronous Promptness Mechanism Example.	**55**
Fig.2.19.	Timing Diagram of the Asynchronous Promptness Example.	**56**
Fig.3.1.	Example of LCM-Based Schedule.	**59**

Fig.3.2.	Example of Memory Reduction-Based Schedule.	**59**
Fig.3.3.	Example of Jitter-Resolving-Based Schedule.	**61**
Fig.3.4.	Performance Comparison between the Three Methods.	**62**
Fig.3.5.	The Planning Scheduler of [Almeida 99].	**63**
Fig.3.6.	The Modified FIP Bus Arbitrator [Almeida 99].	**64**
Fig.3.7.	The Distributed System architecture of [Vasques 94], [Burns 97].	**66**
Fig.3.8.	Typical Networked Control System Model.	**71**
Fig.3.9.	The NCS with Network-Induced Delay.	**71**
Fig.3.10.	Stability Regions for the Second Case of Zhang.	**74**
Fig.3.11.	The Schematic Diagram of the ICCS of [Halevi 88].	**76**
Fig.3.12.	The Timeline Diagram of [Kim 98].	**79**
Fig.3.13.	The End-to-End Design Methodology of [Hong 96].	**80**
Fig.4.1.a	Sequence of Aperiodic Transactions in FIP Network.	**83**
Fig.4.1.b	Sequence of Aperiodic Transactions in FIP Network.	**84**
Fig.4.2.	Example of WCRT of WorldFIP Urgent Aperiodic Variables.	**88**

Fig.4.3.	Simulation histogram of 1000 macrocycles.	**96**
Fig.4.4.	Simulation histogram of 15,000 macrocycles.	**97**
Fig.4.5.	Simulation histogram of 20,000 macrocycles.	**97**
Fig.4.6.	Simulation histogram of 1000 macrocycles of phase 2.	**99**
Fig.4.7.	Simulation histogram of 15,000 macrocycles of phase 2.	**100**
Fig.4.8.	Example of WCRT of Normal aperiodic Variable in FIP.	**103**
Fig.5.1.	Typical FIP system.	**109**
Fig.5.2.	Control loop i with network delays.	**110**
Fig.5.3.	Loop delay of Loop i.	**111**
Fig.5.4.	Example of data rejection and Vacant Sampling.	**112**
Fig.5.5.	Stability region for time varying delayed system vs. constant delayed system	**114**
Fig.5.6.	The duration periodic window slot in FIP system.	**118**
Fig.5.7.	The offered time windows in T_1.	**119**
Fig.5.8.	T_M and its relation to T_1.	**121**
Fig.5.9.	The BAT of Example E.5.1.	**125**

Fig.5.10. The BAT of Example E.5.2. **129**

Fig.5.11. The Closed Loop 1 Model. **130**

Fig.5.12. Actuator input of loop 1. **131**

Fig.5.13. Plant output of loop 1. **131**

List of Symbols and Abbreviations

Symbol	The Meaning
Spi	The Periodic Stream i.
$\mu cy = T_e$	Time length of microcycle.
Mcy	Time length of macrocycle.
HCF	Highest Common Factor.
LCM	Least Common Multiple.
BAT	Bus Arbitrator Table.
WCRT	Worst Case Response Time.
C_{Pi}	The length of the periodic variable i.
C_{Sj}	The length of the aperiodic variable j.
δ_k	The dead time interval length.
$T_{Pi} = T_i$	The period of the periodic variable i.

σ'_{PA}	the overhead incurred with both the polling of the nodes that generate aperiodic variables.
T_S^{MAX}	The cyclic phase or window.
h	The sampling time interval in seconds.
PH_i	The phase of certain process i.
T_{api}	The period of the application process.
t_{max}	The maximum periodic information transmission time.
d_i	The deadline of the process.
Q_o	The size of the ongoing queue.
Q_u	The size of the urgent request queue
Q_n	The size of the normal request queue
R^k_{ua}	WCRT of the Urgent Aperiodic variable.
ABI	Aperiodic Busy Interval.
NABI	Number of microcycles in the ABI.

NP	Number of Periodic variables that are in the BAT.
$\mathbf{Ca_1}$	The maximum transmission time of aperiodic variable.
$\mathbf{Ca_2}$	The maximum transmission time of polling aperiodic variables list.
$\mathbf{\Delta_{aper}}$	Aperiodic traffic in the ABI.
$\mathbf{\Delta_{per}}$	Periodic traffic in the ABI.
$\mathbf{\Delta_{pad}}$	Padding inserted traffic in the ABI.
$\mathbf{Jsp_j}$	maximum communication Jitter of a periodic stream Spj.
$\mathbf{Ya_{11}}$	Time to poll one aperiodic variable.
$\mathbf{Ya_{12i}}$	Time to respond with one aperiodic variable value.
$\mathbf{Ya_{21}}$	Time to poll list of aperiodic variables.
$\mathbf{Ya_{22i}}$	Time to respond with the aperiodic variables list.
$\mathbf{N_A}$	Number of aperiodic variables.

$\mathbf{R^{k}_{na}}$	the Worst Case Response Time of a Normal Aperiodic variable.
$\mathbf{Npp_1}$	Number of periodic variables that are served by the BA while serving the urgent queue, when the urgent request queue is full.
$\mathbf{Npp_2}$	Number of periodic variables that are served by the BA while serving the normal queue, when the normal request queue is full, and after the urgent queue becomes empty.
$\mathbf{N\mu cy_U}$	Number of microcycles passed during the BA serving the urgent queue, when the urgent request queue is full.
$\mathbf{a_1}$	The new urgent aperiodic requests that arrive during serving the full urgent request queue.
$\mathbf{a_2}$	The new urgent aperiodic requests that arrive during serving the full normal request queue.
$\mathbf{NABI_N}$	Number of microcycles that passed in the Aperiodic Busy Interval of the Normal aperiodic variable.
$\boldsymbol{\theta_{SCi}}$	The delay from the sensor to the controller.
$\boldsymbol{\theta_{CAi}}$	The delay from the controller to the actuator.
$\mathbf{D_i}$	The Delay of Loop i.
$\mathbf{L\ (\ t\ )}$	Variable (random) time delay.
$\boldsymbol{\Psi_i}$	The maximum allowable loop delay of loop i.

L''_P	The length of polling packets in bits.
L''_i	The length of responding packet of node i in bits.
bps	Network Speed in bit per seconds.
r_i	maximum number of data windows that can be served during the worst case latency in loop i.
W_i	Periodic window duration.
K	Vector of ratios of sampling times with respect to T1 the smallest sampling time.
α_K	The average number of sampled data during T1.
U_1	The First Mathematical Representation of Periodic Utilization.
U_2	The First Mathematical Representation of Periodic Utilization.
W_a	The maximum time taken to transmit one aperiodic variable.
σ_1	The maximum turnaround time in seconds.
σ_2	The maximum processing time in seconds.

Dedication

To my late Father Nabil, and my Mother Nadia, to whom I must return all my success and who gave me the sprite to continue.

Acknowledgment

I wish to express my profound thanks to both my supervisors Dr. Hany M. El Sayed, and Professor Dr. Ahmed A. Bahnasawi who helped making this work reality. Thanks to Bassem Makram, my soul friend, without his encouragement I might not finish this thesis. Thanks to Eng. Ashraf M. who helped me in understanding the Matlab Simulink program. Finally, I would like to express my appreciation to our God and Lord, who created us and give us the ability to explore our universe.

Abstract

Fieldbus networks are widely used as the communication support for the Distributed Computer Controlled Systems (**DCCS**), or what is referred to as the Integrated Communication and Control Systems (**ICCS**), also known as Network Controlled Systems (**NCS**). Usually there are many control loops that are attached to the fieldbus common bus. The applications of the Fieldbuses have a wide range from the process control to the discrete manufacturing; in addition to that fieldbus are used in Textile Industry, Home Automation, Trains, Mining Industry, and Automotive Applications. There are Real-Time constraints that are imposed by the DCCS onto its communication network (Bus), which means that the traffic of the periodic and sporadic must be bounded within a well-defined time interval; otherwise a timing fault occurs, which may lead to critical situations. This motivates the designers to use special types of communication networks in which the Medium Access Control (**MAC**) protocol is able to schedule the different types of traffic according to their real-time requirements.

In this thesis we review the history of the Distributed Computer Controlled Systems communications which are used to connect the industrial systems. We introduce the definition of the term "fieldbus" and its relation to the OSI network. Finally and before we compare various types of the fieldbuses, we demonstrate three fieldbus protocols.

We go through the main FIP protocol specifications especially, the ones that are related to the real-time requirements. Then we demonstrate many real-time studies that were done on the FIP protocol, like the change of the scheduling method of the FIP. We concentrate on the real-time aspects of the aperiodic FIP traffic, like the estimation of the Worst Case Response Time (**WCRT**) of the FIP's aperiodic traffic, and the stability of the closed-loop systems that are attached to the FIP common bus.

Our main objective in this thesis is to analyze the appropriate scheduling algorithms to guarantee before the run-time that the real-time constraints of the FIP-based distributed computer controlled systems (DCCS) are easily verified.

In this thesis, we analysis the Data Link Layer (DLL) of the WorldFIP in order to formulate an enhanced analytical formula for the evaluation of the Worst Case Response Time of both types of the aperiodic variables (Urgent and Normal Aperiodic variables) in the FIP. The WCRT is a powerful metric in analyzing the real-time system requirements. Then we verify our formula using a simulation test program that simulates the FIP network traffic.

There is another main objective of this thesis which is how to preserve the control closed-loop system stability of each one of the control loops that is attached to the FIP common bus. We propose a modified scheduling algorithm in order to guarantee the stability of those closed-loop control systems. In addition we refine our proposed scheduling algorithm to assure there will be enough time available for the aperiodic traffic. At the end, we study the performance of our modified algorithm using the Matlab Simulink simulator.