A Fully-Integrated Adaptive Temperature-Compensating Ethernet Equalizer for Automotive Applications

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ULSAN NATIONAL INSTITUTE OF SCIENCE AND TECHNOLOGY

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Seulkirom Kim

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Approved by

Advisor

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by Seulkirom Kim

Abstract

In this paper, the Ethernet equalizer that compensates automotive temperature range is presented. More and more, the communications in automotive are important because of many electronics in the vehicle. Ethernet protocol can be candidate of automotive communications. However it should satisfy AEC-Q100. For meeting AEC-Q100, it should have an operational temperature range from -40 degree to 150 degree. This paper proposes the Ethernet equalizer that can recover the data until 100m CAT-5 cable adaptively at -40 degree to 150 degree. For supporting the wide temperature range, feedback system is used. The proposed equalizer has 31.25 MHz bandwidth and a fully-differential structure. The proposed automotive Ethernet equalizer is implemented in a Hynix 0.13 um BCDMOS technology.

Acknowledgement

Beyond all, I would like to express my appreciation to adviser professor, Franklin Bien. I could have an internship opportunity in July 2014. He gave me conviction during the internship term that I would grow up with professor Bien. Even though I didn't have any relationship in Ulsan, I could get into UNIST thanks to professor Bien. Because he taught lots of stuffs which I should keep in mind while researching, now I feel I established a great foothold to proceed to real field of electrical engineering.

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마지막으로 2년간 먼 거리에서도 한결같이 응원해준 여자친구에게 이 논문을 바칩니다.

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Abbreviations

MCU	Machine Control Unit
ECU	Electronic Control Unit
LIN	Local Interconnect Network
CAN	Controller Area Network
CAT-5	Category 5
100BASE-TX	100 Mbps Baseband communication Twisted Pair cable
AEC	Automotive Electronics Council
AEC-Q100	Failure Mechanism Based Stress Test Qualification for Integrated Circuits
EMI	Electro Magnetic Interference
ESD	Electrostatic Discharge
MOSFET	Metal Oxide Silicon Field Effect transistor
TX	Transmitter
RX	Receiver
MLT-3	Multi-Level Transmit 3
HPF	High Pass Filter
LPF	Low Pass Filter
FIR	Finite Impulse Response

VGA	Variable Gain Amplifier
CMFB	Common mode Feedback
PGA	Programmable Gain Amplifier
CTLE	Continuous-Time Linear Equalizer
DTLE	Discrete-Time Linear Equalizer

Chapter I

Introduction

1.1. Electronics and communications in automotive

Traditionally, the automotive has been in area of mechanical engineering. A lot of mechanical components are controlled by MCU (Machine Control Unit). Many mechanical components and MCU were important part in the automotive. But now, most of components in automotive controlled by ECU (Electronic Control Unit). ECUs control the mechanics and electronics. Also ECUs diagnose the state of vehicle using sensor and inform a danger to the driver.

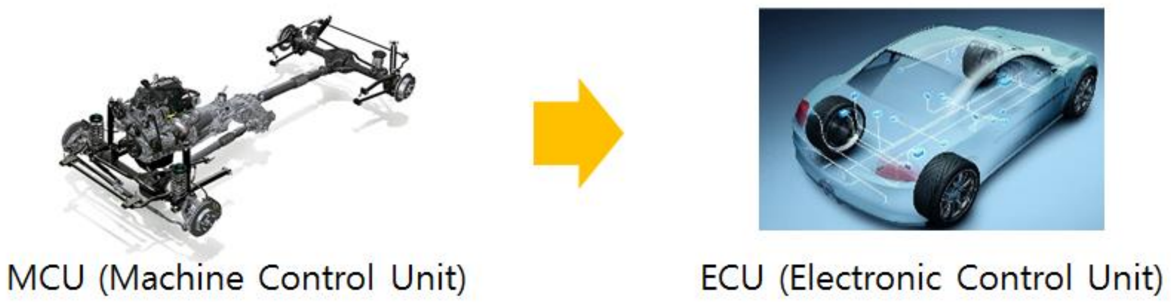

Figure 1-1: Automotive control method moving from MCU to ECU

Let us check which functions controlled and operated by ECU in the automotive. First one is powertrain part. Electronics control the transmission and engine which are a most important part in the vehicle. Chassis is also important part. Electronics control the brake and steering systems. Also lighting, wipers and sunroof in body part are controlled by electronics. In the automotive electronics, Infotainment is important. Infotainment is information and entertainment. It means like navigation system and audio and video. It need high data rate for providing high quality of driver's convenience. In the past, automotive just was mean of transportation. But now, automotive is one of electrical appliances. There are a lot of convenient functions for driver [1].

Figure 1-2: Automotive moves from transportation to electrical appliance

We checked electronics in the automotive. ECUs should communicate with others ECUs in automotive. In vehicle network between electronics is important. In the future, automotive also should communicate with infrastructure and another automotive. Vehicle to vehicle communication is needed for autonomous car. More and more, automotive communication is important.

1.2. Communication protocols in automotive

Until now, most typical automotive communication protocols are LIN (Local Interconnect Network) [2] and CAN (Controller Area Network) [3]. LIN has a 20 kbps data rate. Because it is cheap and simple, LIN is used in applications that speed is not important like sunroof, mirror control and wipers. CAN has a 1 Mbps data rate. It has high reliability and efficient controller. But it almost closes to limitation of bandwidth because of increasing node per vehicle. Flex Ray can be the next generation automotive communication protocol [4]. But it is expensive to setup whole system and has not too wide bandwidth. Flex Ray has just 10 Mbps. It can be used in steering, active suspension and traction control systems. However, multimedia is increasing in Automotive and real-time is important for driver safety. Flex Ray and MOST [5] are not enough to be next automotive communication protocol.

So, Ethernet is most perfect candidate as automotive communication protocol [6]. It has a 100M bps. As we know, Ethernet is common communication protocol in the world. It is used widely already in the internet system. Ethernet is not expensive because of standard in the internet system. Also Ethernet has biggest advantage. It can supplies IP system. If automotive can have an IP address, it can be applied to various application in automotive like smart navigation system and autonomous vehicle. As a result, Ethernet is needed for automotive application.

Bus Systems	**Features**
LIN (Local Interconnect Network)	- 20 kbps data rate - Serial bus system and low cost - Use in Applications that speed is not important - Sunroof, mirror control and wipers
CAN (Controller Area Network)	- 1 Mbps data rate - High reliability and efficient controller network - Relatively wide bandwidth. But, close to limitation of bandwidth - Powertrain, ABS, engine control
Flex Ray	- 10 Mbps data rate - New generation communication protocol can be replaced with CAN - But, expensive and not too wide bandwidth - Steering, Active suspension and Traction control
Ethernet	- 100 Mbps data rate - Wide bandwidth and inexpensive - Standard that has been used successfully for years now in networking - Infotainment, camera and radar system

Table 1-1: Comparison of communication protocol in automotive

Let us talk about the Ethernet more. I will deal with a 100BASE-TX protocol in Ethernet. 100 means 100 Mbps data rate, and BASE means baseband communication. TX is unshielded twisted pair cable that we call the UTP. It should support data transmission until 100m cable. UTP cable named Category-5 has a frequency response same with a low pass filter. In the long length cable, it is possible to loss data [7].

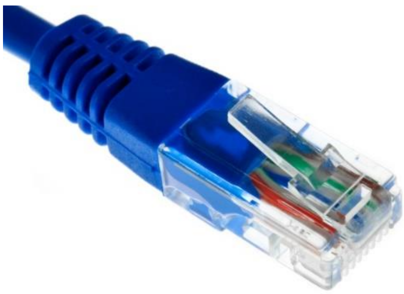

Figure 1-3: Unshielded twisted pair (UTP) cable, Category-5

100BASE-TX should support data transmission until 100m cable. However, non-ideal transmission channel causes signal distortion. Let us image that impulse is sent to the 10m cable. Data transmission almost is perfect. In 50m cable, also signal distortion is not too big problem. Even though signal distortion happens, data can be recovered same with input signal. But in a 100m cable, signal is degraded too much. In this situation, wrong data transmission is possible. So we need a data compensating block after signal distortion caused by long cable length. That is equalizer. Equalizer is essential block in Ethernet system. This paper proposes automotive Ethernet equalizer design for 100BASE-TX [6].

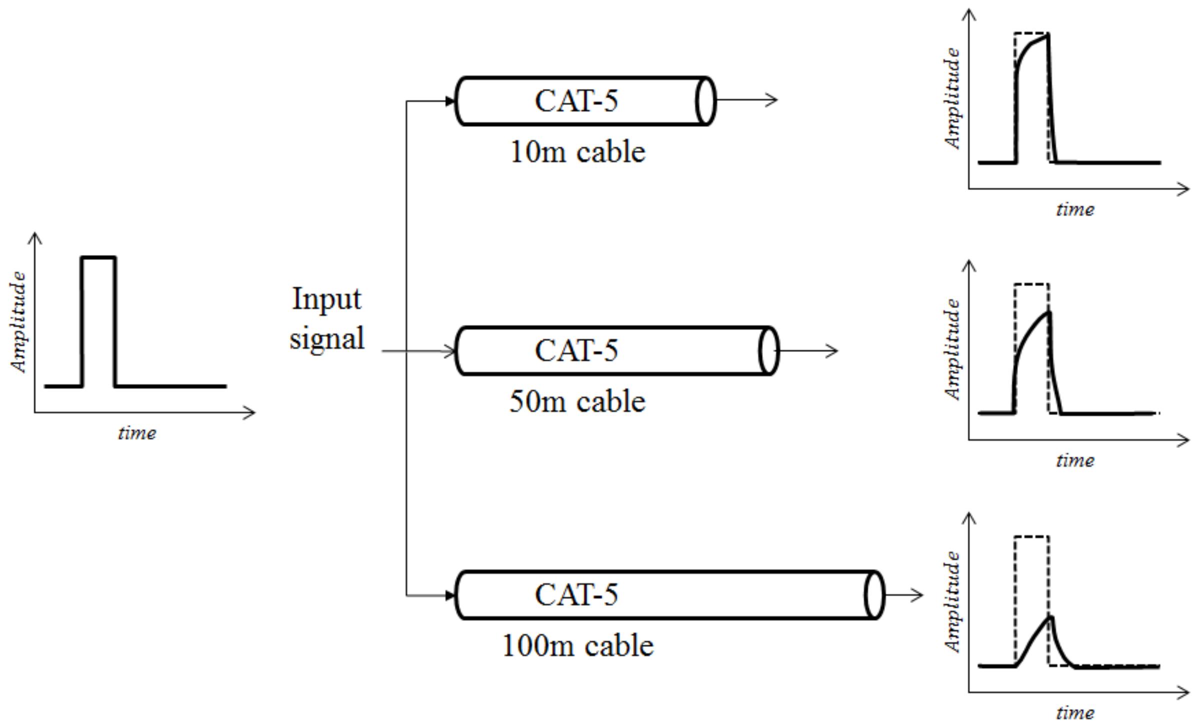

Figure 1-4: Signal distortion depend on cable length

1.3. Automotive temperature range for AEC-Q100

In this paper, design target is Ethernet equalizer for automotive applications. IC for automotive should meet an AEC-Q100. It is made by the Automotive Electronics Council (AEC) was originally established by Chrysler, Ford, and GM. AEC-Q100 is for the purpose of establishing common part-qualification and quality-system standards. It means Failure mechanism based stress test Qualification for integrated circuits. AEC-Q100 should meet stress tests under the extremely temperature range, humidity, vibration, EMI/ESD, life time and etc. In these, most difficulty to satisfy is temperature. Humidity and vibration can be covered by packaging techniques. IC designer should concentrate an operating temperature.

Let us compare with other applications. The consumer electronics has operating temperature range from 0 to 85 degree. The industrial electronics has wide range than consumer electronics. But automotive should operate from -40 to 150 degree. It is hard to satisfy to operate well. In this paper, Adaptive temperature-compensating Ethernet equalizer is described.

Parameter	**Automotive**	**Consumer**	**Industrial**
Operating Temperature	-40℃ ~ 150℃	0℃ ~ 85℃	-10℃ ~ 125℃
Product Life Span	> 10 years	1 ~ 3 years	5 ~ 10 years
Humidity	0 ~ 100%	50%	Environmental
Allowable	Zero Defect	3%	Less than 1%
Supply Commitment	> 30 years	> 2 years	> 5 years

Table 1-2: Comparison of automotive electronics with other electronics

Chapter 2

Limitations of Ethernet Equalizer for Automotive Applications

2.1. Background of equalizer

Before explaining about limitation of automotive Ethernet equalizer, it should be first to study the equalizer basic concept. When signal is sent through the channel, signal distortion happens. In this situation, the equalizer compensates a signal degrading.

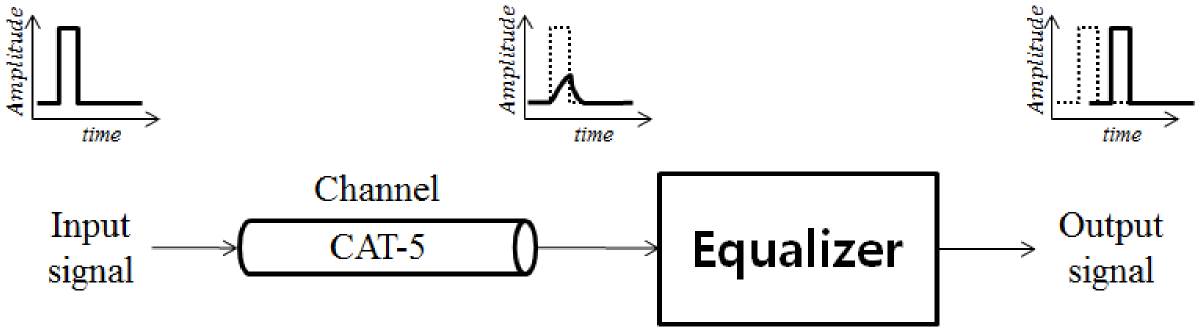

Figure 2-1: Concept of equalizer

Let us check in a frequency domain. A cable frequency response is same with a low pass filter. If cable length is long, cut-off frequency is low. After channel, high frequency components is degraded. In this situation, if degraded signal after channel passes though block that has a frequency response same with a high pass filter, the output frequency response will be flat. An equalizer frequency response is similar with a high pass filter. It is compensate a high frequency components. But it is impossible that there is ideal flat frequency response in real world. A dot plot in figure 2-2 is real equalized frequency response. The special frequency is amplified and signal distortion is compensated. This is concept of equalizer.

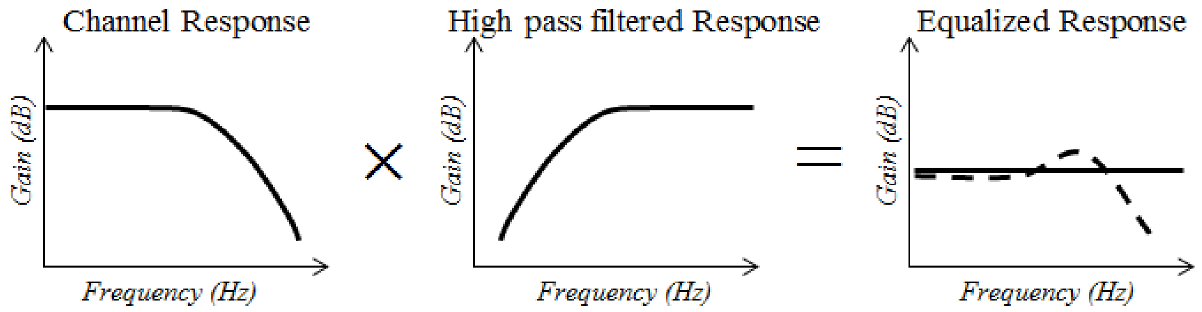

Figure 2-2: Frequency response of channel and equalizer

2.2. Limitations of Ethernet equalizer in automotive operational temperature range

Already there are many Ethernet equalizer without temperature compensating. But it cannot be apply to automotive applications because of wide temperature range. This paper proposes temperature compensating Ethernet equalizer for automotive applications.

The limitations of automotive Ethernet equalizer is operational temperature range. When temperature is changed, electron and hole mobility is also changed. Because phonon scattering is increased with temperature increasing, electron and hole are hard to move. It means mobility decreasing. On the other hand, when temperature is decreased, mobility will be increased [8]. Also it can be reason to change a MOSFET threshold voltage.

Because of temperature changing, the device characteristic is also changed. A MOSFET performance is improved at low temperature. A MOSFET can get the high transconductance result from high current driving. Also parasitic resistances and interconnection metal resistances are decreased. On the other hand, MOSFET performance is decreased with high temperature [9].

This phenomena makes circuit amplification factor different. That is not critical in amplifier which makes more than 60dB. But it is important factor in amplifier which makes less than 20dB like an equalizer. It should be compensated.

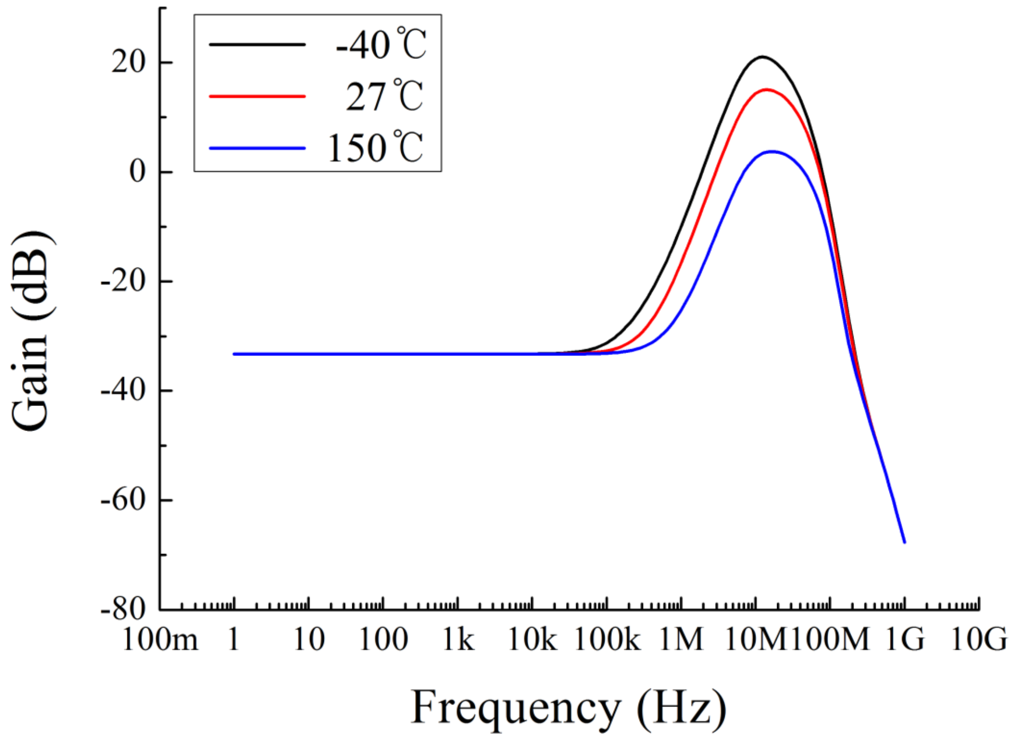

Figure 2-3: Frequency response of equalizer depend on temperature

Figure 2-3 is frequency response of equalizer depend on temperature. The red line is target frequency response at 27 degree. This equalizer has a 17dB at target frequency. But if temperature is decreased to -40 degree, target frequency amplification factor is increased to 20dB. Whereas, equalizer that designs to have a 17dB amplification factor is changed to 3dB. The difference between -40 degree case and 150 degree case is almost 20dB. We can check this situation in time domain. Figure 2-4 is well equalizing waveform. But at low temperature (-40 degree, figure 2-5), we can check over equalizing because of high mobility. In this situation, state of ‘0’ cannot be detected. On the other hand, under equalizing is possible at high temperature (150 degree, figure 2-6). In under equalizing situation, state of ‘-1’ and ‘1’ cannot be detected. As a result, if temperature is changed to high or low, wrong data transmission is possible. That is not simple communication problem. The error caused by temperature can be threat for driver. It should be covered adaptively depend on temperature variation.

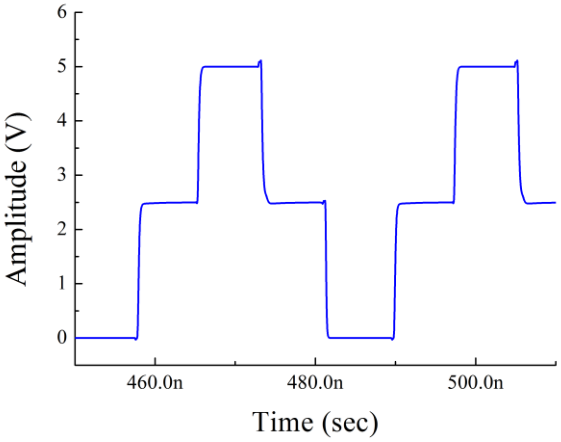

Figure 2-4: Normal equalizing waveform at 27 degree

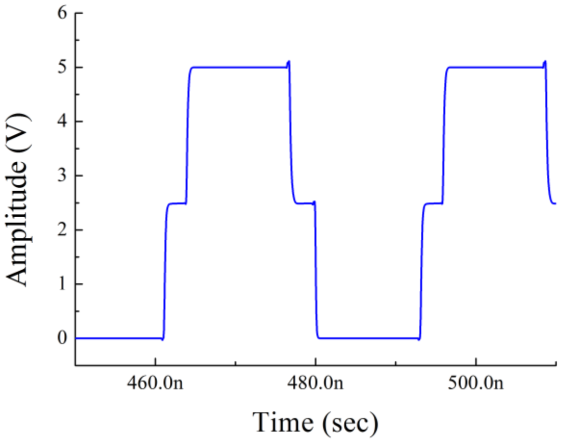

Figure 2-5: Over equalizing waveform at -40 degree

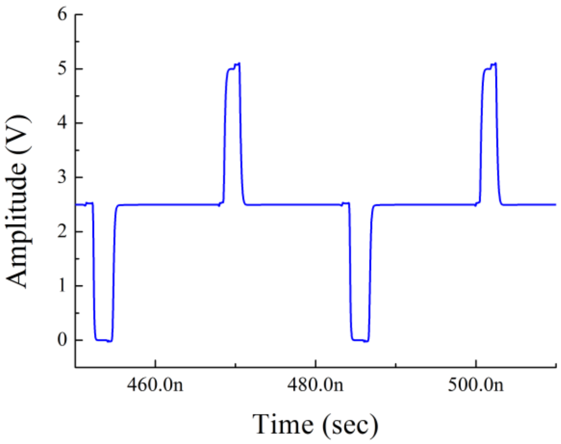

Figure 2-6: Under equalizing waveform at 150 degree

2.3. Ethernet physical layer structure for avoiding baseline wander

The baseline wander also can be one of limitations for automotive Ethernet equalizer. Data is sent in 2 level system, ‘0’ and ‘1’. In this time, if data transition happens from ‘0’ to ‘1’ or reverse case, baseline after channel is stable. But if same data is sent repeatedly like figure 2-7, received baseline is going up or down. This is critical problem in data transmission and recovering. Commonly, an equalizer uses stable reference voltage for comparing to signal level. However baseline is changed up, recovered data can be ‘1’ irrespectively with sending data. Also baseline is going down because of ‘0’ repetition, equalizer detect it to ‘0’ although transmitter sends data ‘1’.

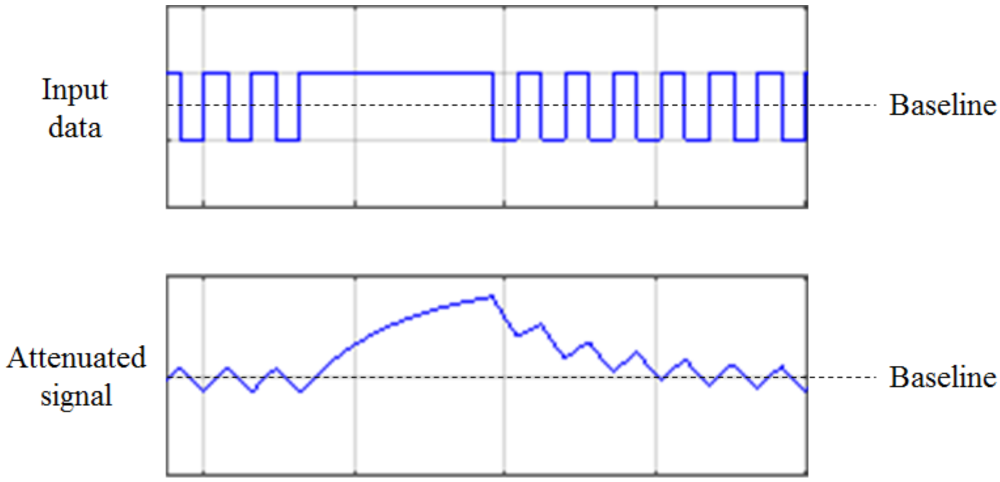

Figure 2-7: Baseline wander situation

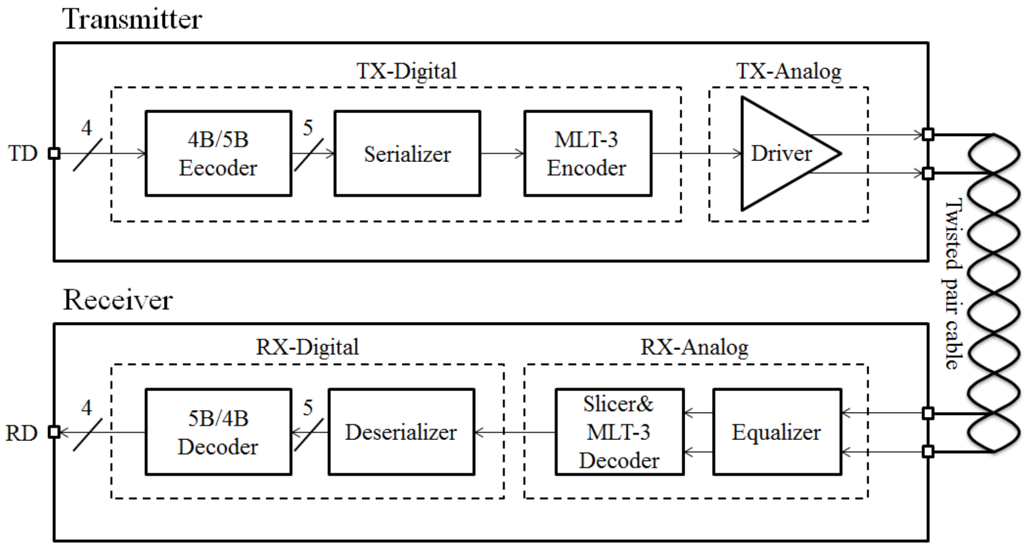

Figure 2-8: Block diagram of Ethernet physical layer

In order to solve the baseline wander, Ethernet uses the two techniques. First one is 4bits to 5bits encoding and second one is MLT-3 encoding. Figure 2-8 is Ethernet PHY block diagram. At first, 4 bits parallel data comes to transmitter. Using 4 bits to 5bits encoder, that 4bits parallel data is transferred to 5 bits parallel data. Because of this block, 100 Mbps changes to 125 Mbps. Serializer makes series data from 5 bits parallel data. After serializing, signal is encoded to MLT-3 signal though the MLT-3 encoder. And driver sends the signal to channel named category-5. This step is data transmission in Ethernet PHY transmitter. The receiving steps are same with transmitting steps in Ethernet PHY receiver. Just steps are reversed without equalizer. The equalizer compensates signal distortion and recovers the data.

4 bit data	5 bit data	4 bit data	5 bit data
0000	11110	1000	10010
0001	01001	1001	10011
0010	10100	1010	10110
0011	10101	1011	10111
0100	01010	1100	11010
0101	01011	1101	11011
0110	01110	1110	11100
0111	01111	1111	11101

Table 2-1: 4 bits to 5 bits encoding

So, we should think why 4 bits to 5 bits encoding and MLT-3 encoding is used. Both techniques are used for avoiding baseline wander. Firstly, 4 bits to 5 bits encoding is technique to avoid ‘0’ repetition. Table 2-1 is transfer table of 4 bits to 5bits encoding. If ‘0000’ will come to encoder, result is ‘11110’. And ‘0001’ and ‘1000’ are changed to ‘01001’ and ‘10010’. As a result, ‘0’ repetition is reduced to only 2 times. As we can check, results of encoding can has 3 times ‘0’ repetition. ‘10100’ to ‘01001’ sequence is most extreme situation.

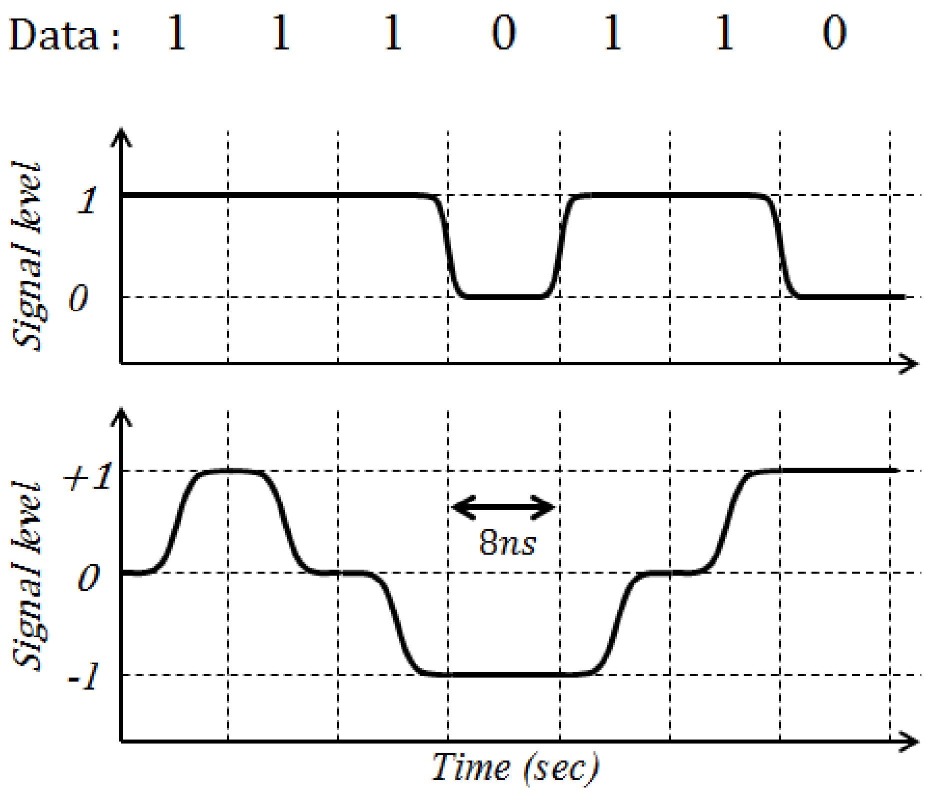

Figure 2-9: MLT-3 encoding waveform

Next, how can ‘1’ repetition be avoided. The baseline wander caused by ‘1’ repetition MLT-3 encoding can be solved using MLT-3 encoding. The MLT-3 is multi-level transmit and 3 means 3 voltage level. The common data uses two level system. It has two bits just ‘0’ and ‘1’. However, MLT-3 has a 3 level, ‘1’, ‘0’ and ‘-1’. When ‘0’ bit comes from common data system, MLT-3 encoder has no transition. That keeps same level with a before. And when ‘1’ bit comes in, level transition happens to next level. If signal level comes from ‘1’ to ‘0’ like figure 2-9, the next transition is to the ‘-1’ signal level. Using MLT-3 encoder, ‘1’ repetition is solved. It is meaningful that both 4 bits to 5bits encoding and MLT-3 encoding use together only.

Because of the steps, the Ethernet equalizer should compensate MLT-3 signal. It is different with a 2 level data transmission. MLT-3 waveform also one of difficulty of equalizing.

Chapter 3

Implementations of Proposed Automotive Ethernet Equalizer

3.1. Continuous-time linear equalizer

To compose proposed automotive Ethernet equalize, continuous-time linear equalizer is used. There are two type of equalizer, discrete-time linear equalizer and continuous-time linear equalizer.

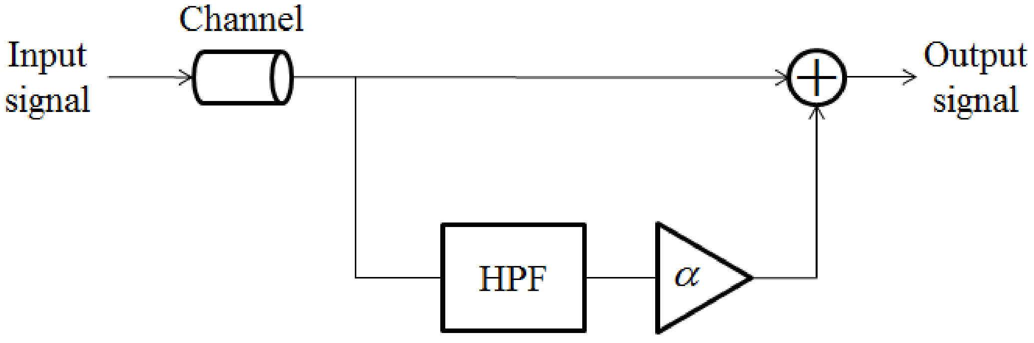

Figure 3-1: Block diagram of continuous-time linear equalizer

Discrete-time linear equalizer uses a FIR filter. It uses more than four delay cell and amplifies each signal. Each amplified signals are added and signal is compensated. It needs a more than four delay cells and gain amplifier. Discrete-time linear equalizer also needs precise delay value and gain. Continuous-time linear equalizer is simpler than discrete-time linear equalizer. The distorted signal after channel has two path. One is going to adder and the others is to high pass filter. After high pass filter, it is sifted that only high frequency components. It is amplified and added with a distorted signal using voltage adder.

Discrete-time linear equalizer can be programmed easily and can make a high performance than continuous-time linear equalizer. But discrete-time linear equalizer spends more power than continuous-time linear equalizer. And signal time delay can be possible. The continuous-time linear equalizer is simple and low power consumption. As a result, it is suitable to apply to automotive equalizer. This paper uses a continuous-time linear equalizer for composing proposed idea. Automotive equalizer using discrete-time linear equalizer is mentioned in future work.

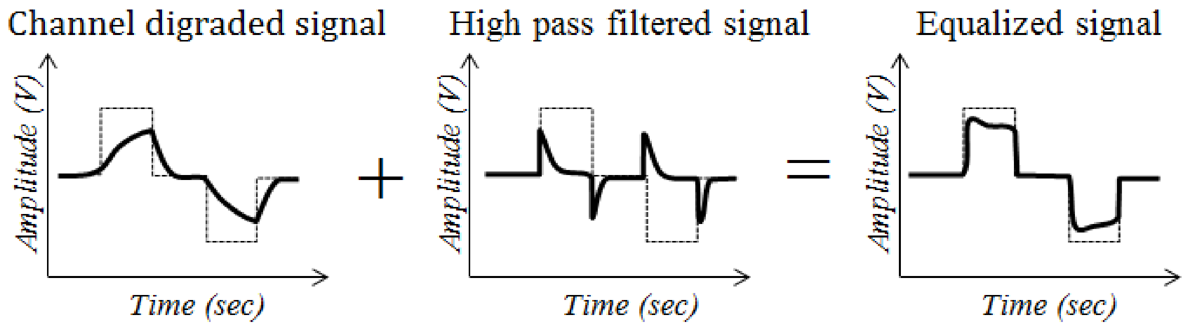

Figure 3-2: Concept of continuous-time linear equalizing

3.2. Proposed adaptive temperature-compensating Ethernet equalizer for automotive applications

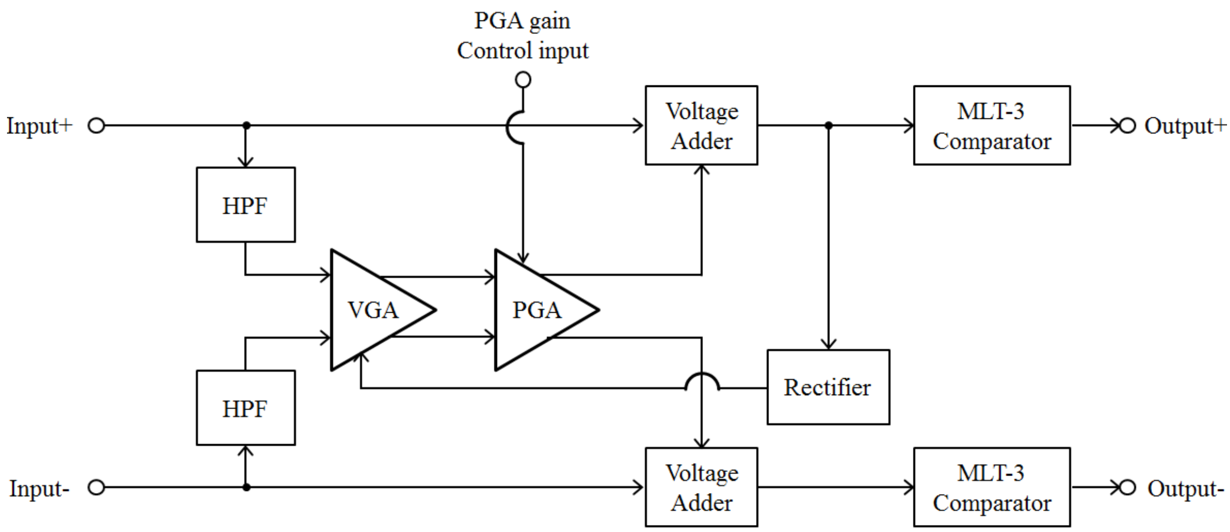

Figure 3-3: Block diagram of proposed Ethernet equalizer for automotive applications

Figure 3-3 is proposed automotive Ethernet equalizer block diagram that can compensate temperature changing in automotive applications. In this paper, continuous-time linear equalizer is used for wide automotive temperature range because of simple. It comes to equalizer that degraded signal has different distortion depend on channel length. That signal goes to voltage adder and high pass filter. This data is transferred to 125 Mbps from 100 Mbps in 4 bits to 5 bits encoder. Because the MLT-3 signal transition needs 8 ns, waveform has 31.25 MHz operational frequency. For compensating 31.25 MHz, high pass filter is designed to have lower cut off frequency than 31.25 MHz. The sifted signal after high pass filter is amplified using two amplifiers, VGA and PGA. Variable Gain Amplifier (VGA) controls the gain for compensating temperature. Programmable Gain Amplifier (PGA) controls the gain depend on cable length. PGA should be controlled to have 20dB gain in 100m cable case. It will be described in detail at implementation part. Amplified signal after PGA goes to the voltage adder. Voltage adder adds amplified signal from PGA and distorted signal from channel. Added signal can have steeper rising time than before. And then, MLT-3 comparator decides signal level. But if added signal amplitude is not enough large because of high temperature, MLT-3 comparator cannot decide each voltage level. In high temperature, each blocks amplification factor is decreased. In this time, added signal amplitude is detected using rectifier [10]. Rectifier changes AC signal to DC signal. If added signal amplitude is decreased because of high temperature, rectifier output DC level is also decreased. In the situation, decreased amplitude should be compensated. Rectifier output is connected with VGA control input. If rectifier output level is decreased, VGA controls the gain higher. In low temperature situation, added signal amplitude and rectified voltage level is increased. As a result, VGA makes lower gain than before. VGA is designed to have 0dB in normal temperature, 27 degree.

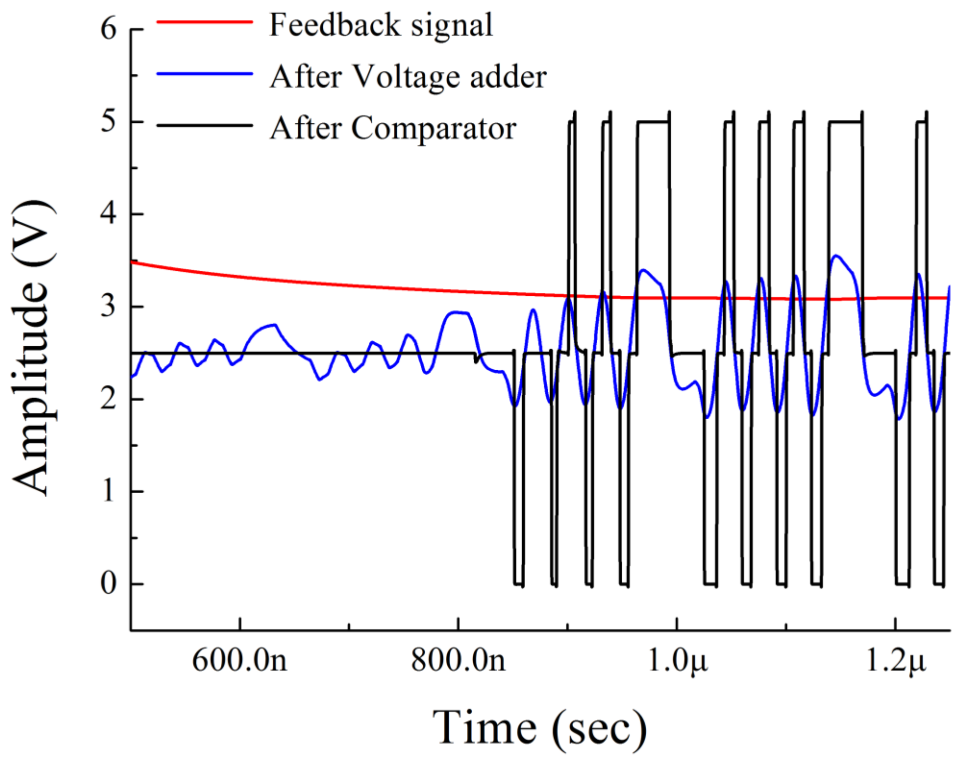

Figure 3-4: Proposed system transient simulation

Figure 3-4 is transient simulation result of proposed automotive temperature compensating Ethernet equalizer. The blue line is added signal after voltage adder. Its amplitude is not enough to be detected until 800 n sec. The red line is feedback signal from rectifier output to VGA control input. When feedback value is as low as almost 3V and stable, added signal after voltage adder has an enough amplitude to be detected in MLT-3 comparator. Until 900 n sec, MLT-3 comparator output, the black line cannot compensate well. But after 900 n sec, it is compensated well.

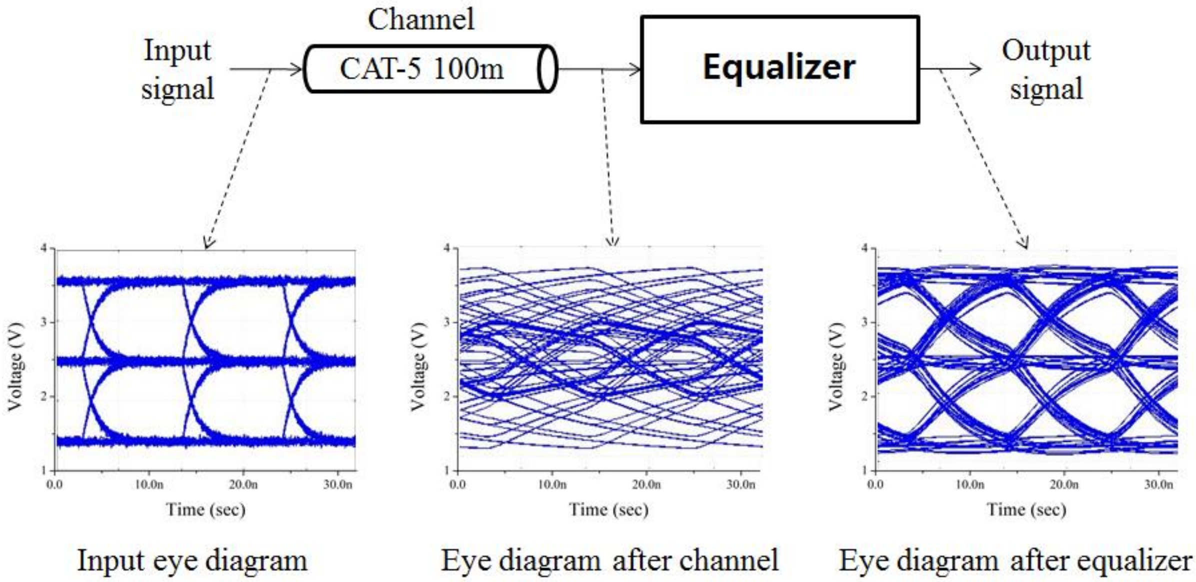

Figure 3-5: Eye diagram simulations of proposed automotive equalizer modeling

Before designing on circuit level, it is simulated at system level. It is modeled by Matlab (Simulink). Figure 3-5 is eye diagram simulation results of proposed system model. The Input signal eye diagram is totally opened. But it is passed by channel that has 6.6 MHz cut off frequency (100m cable model), eye diagram is closed totally. As we can check, Equalized signal eye diagram is opened almost. Depend on this results, proposed automotive temperature compensating Ethernet equalizer is verified as system level.

3.3. Implementations of proposed adaptive temperature-compensating Ethernet equalizer for automotive applications

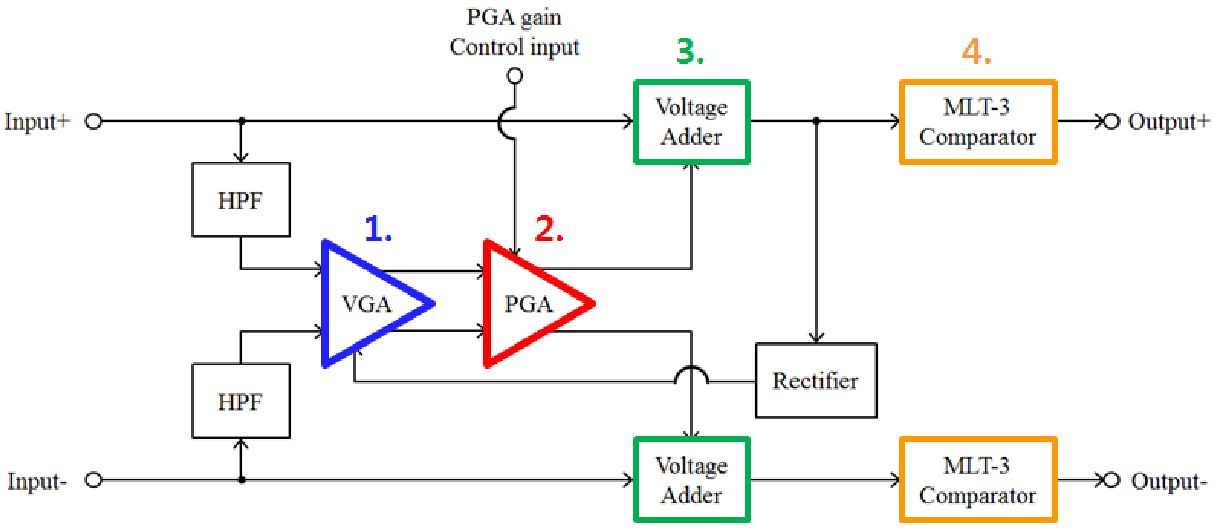

Figure 3-6: Important blocks in proposed Ethernet equalizer for automotive applications

In this part, Implementation of proposed automotive temperature compensating Ethernet equalizer is described. To compose proposed automotive Ethernet, there are four important parts, VGA, PGA, voltage adder and MLT-3 comparator. First one is variable gain amplifier. It is main block in my proposed equalizer for compensating temperature. It should have a linear gain variation in small control voltage change. And if control voltage is changed much, it should have an exponential gain variation. Second one is programmable gain amplifier. It provides four level gains for variable cable length. Next is voltage adder. Voltage adder adds a signal after channel and amplified signal after PGA. Because MLT-3 comparator have a fixed reference value, voltage adder's output common mode level stability is important. Last one is MLT-3 comparator. MLT-3 comparator is different with a common comparator because of 3 level system. From next pages, each blocks will be described.

3.3.1. Feedback system design for adaptive temperature compensating

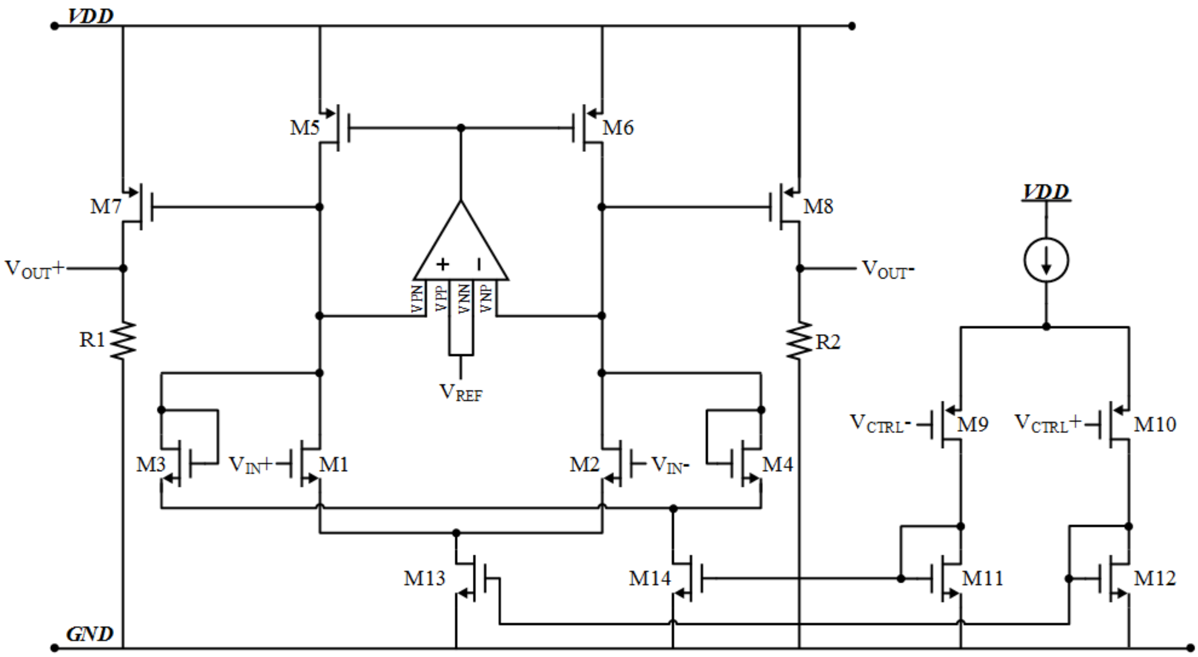

Figure 3-7: Schematic of variable gain amplifier in proposed equalizer [11]

The used variable gain amplifier in proposed equalizer is controlled by current steering. For controlling the gain, two control voltage are needed. They are inversed value based on value that rectified DC voltage level at 27 degree. If $V_{CTRL}+$ is decreased, the current in M10 is increased. Because $V_{CTRL}-$ is reversed value with $V_{CTRL}+$, $V_{CTRL}-$ is increased than before and the current in M9 is decreased. So, the current in driving gate MOSFETs, M1 and M2 is increased and the current in diode connected MOSFETs, M3 and M4 is decreased. As a result, Amplifier gain is creased. In this variable gain amplifier, common mode feedback is used for stability. Because of common mode feedback in first stage, amplifier's gain and output common mode level are stable even though temperature is changed from -40 degree to 150 degree.

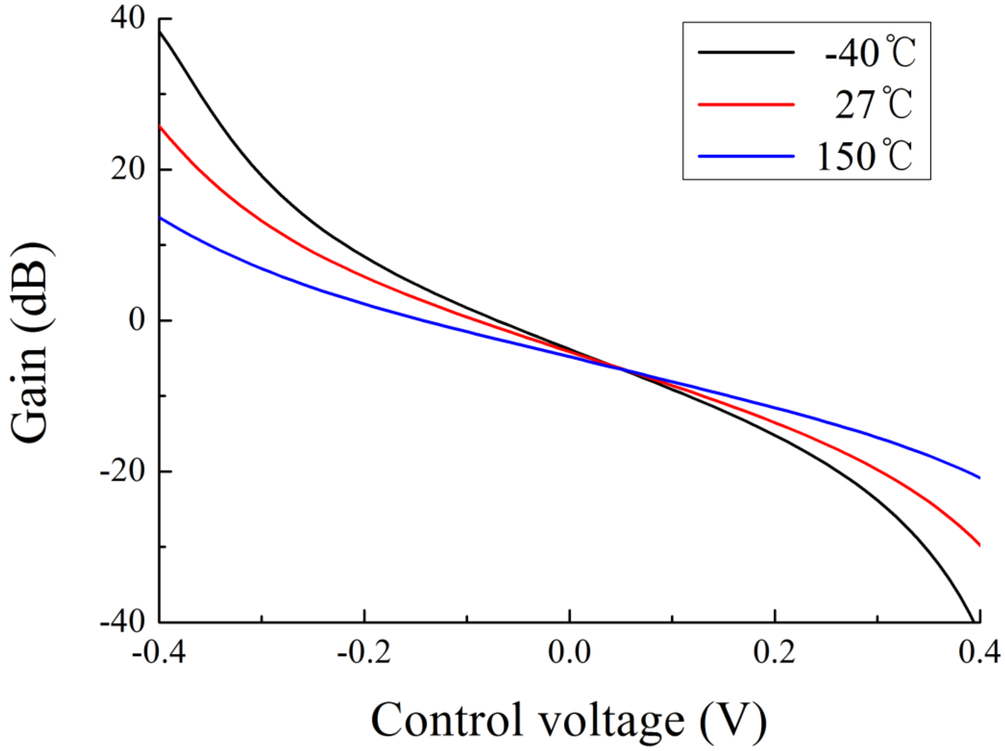

Figure 3-8: Simulation result of variable gain depend on control voltage

Figure 3-8 is simulation result of variable gain depend on control voltage. As I mentioned in last chapter, when temperature is changed, gain also is changed. The amplifier gain is decreased at 150 degree and gain is increased at -40 degree. Even though gain is changed, the VGA provide gain range more than 20 dB. Also, The VGA has a linear gain variable in 0 control voltage and has an exponential gain variable in edge of control voltage. As a result, VGA can change a gain in extreme temperature change situations.

3.3.2. Reconfiguration gain design for various cable length

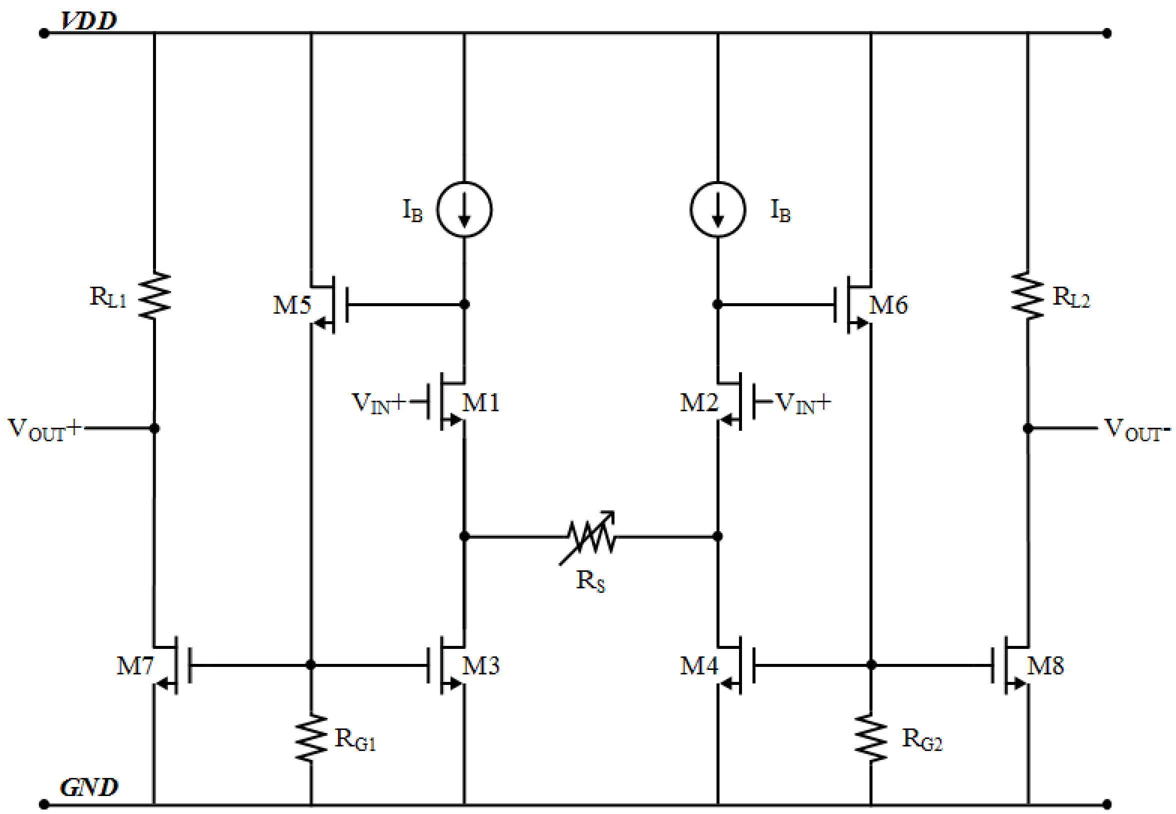

Figure 3-9: Schematic of programmable gain amplifier in proposed equalizer [12]

Ethernet communication should support until 100m cable length. Because of cable, signal distortion happens and it is different depend on cable length. The proposed equalizer has a programmable gain amplifier. The PGA uses a source degeneration. It is designed to have four resistors for gain level, 0 dB, 11 dB, 14 dB and 20 dB. The 0 dB mode is used in 0 m ~ 30 m cable length. The 11 dB mode is used in 30 m ~ 50 m cable length. The 14 dB mode is used in 50 m ~ 80 m cable length. The 20 dB mode is used in 80 m ~ 100 m cable length. This amplifier has three stages because of low amplification factor and it also has a feedback for stability.

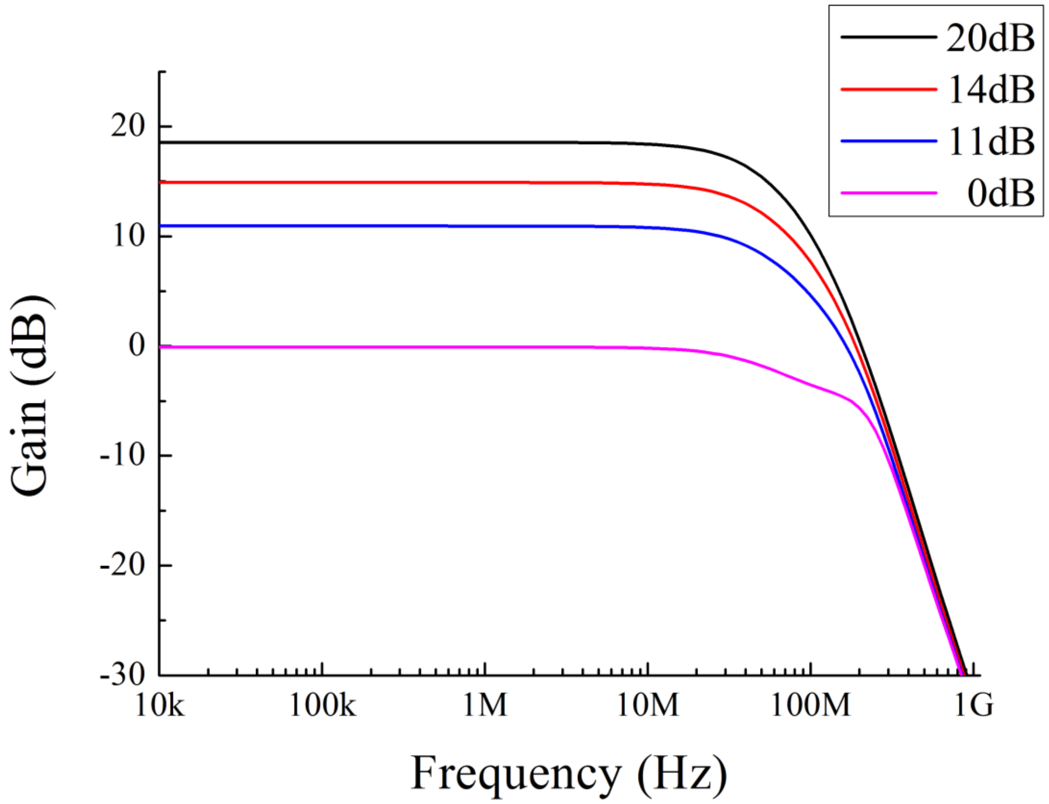

Figure 3-10: Frequency response simulation result of PGA gain depend on programmed resistor

Figure 3-10 is frequency response of programmable gain amplifier. It has four gain modes, 0 dB, 11 dB, 14 dB and 20 dB. The black line is 20 dB mode frequency response. Even though it is less than 20 dB, it is enough to provide until 100 m cable length. The red line in the graph is 14 dB mode frequency response and the blue line is 11 dB mode frequency response. The pink line is 0 dB mode frequency response. This mode provides 0 dB gain in 0 m cable length case. It should be stable.

3.3.3. Voltage adding design for output common mode stability

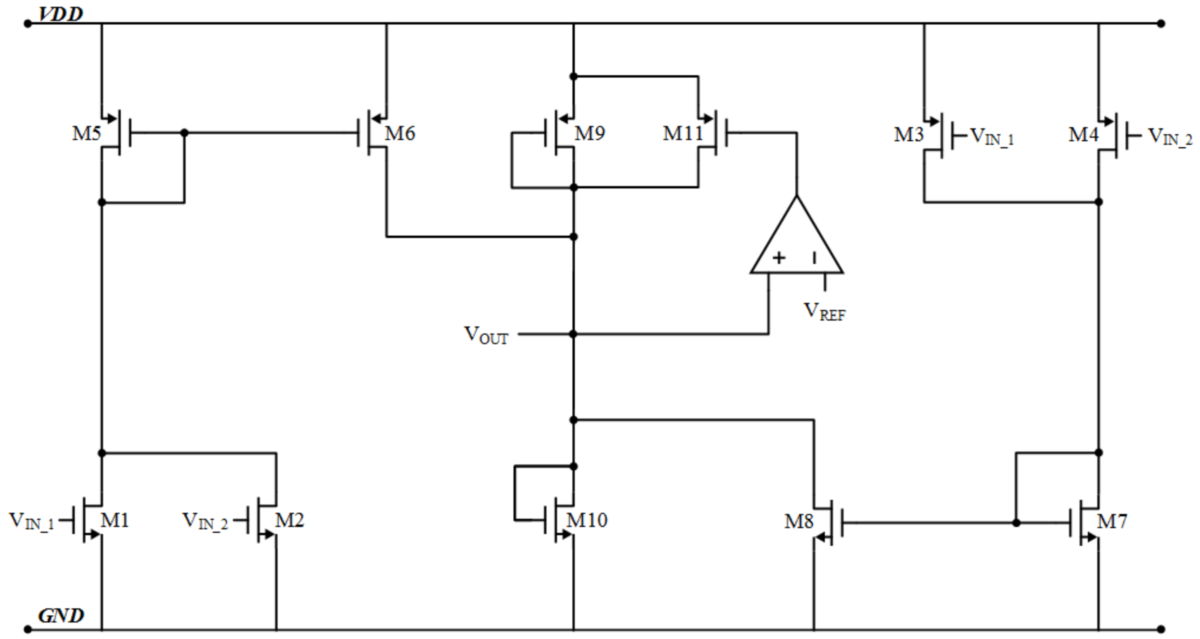

Figure 3-11: Schematic of voltage adder in proposed equalizer

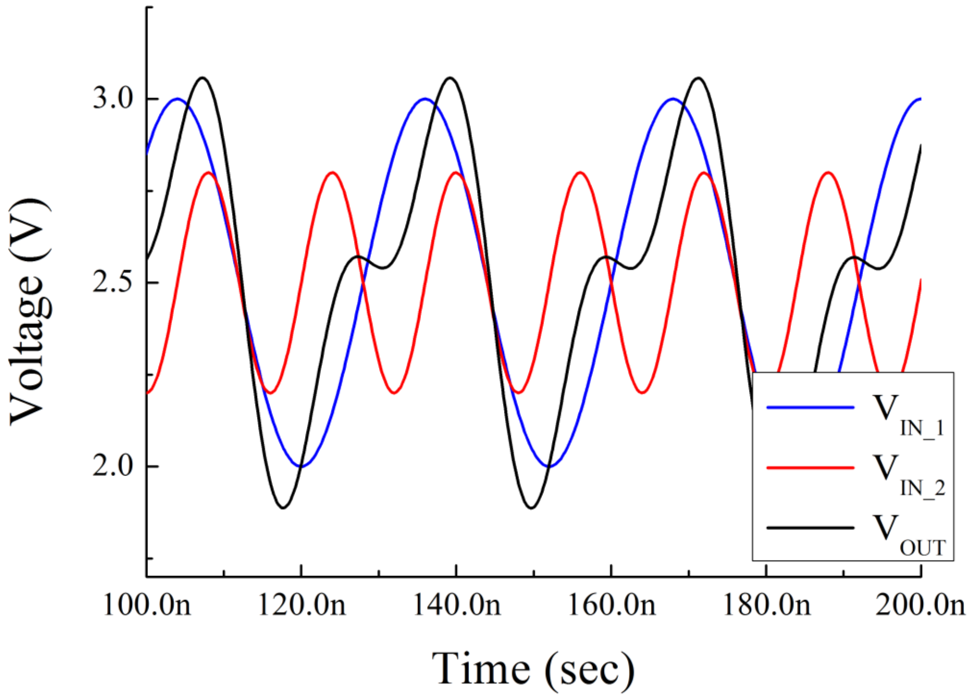

Figure 3-12: Transient simulation result of voltage adder

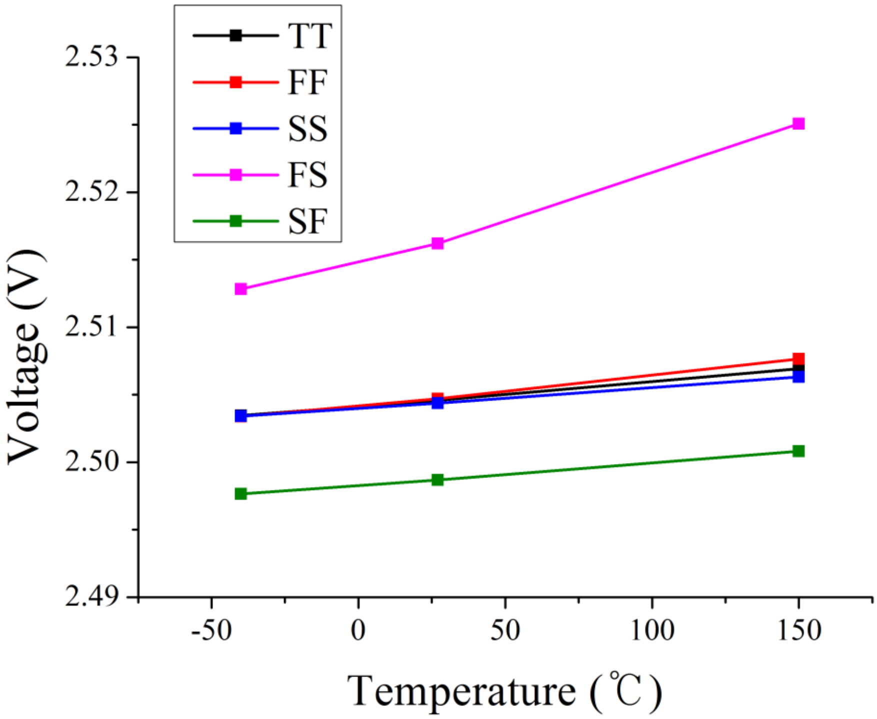

Figure 3-13: Simulation result of voltage adder common mode level depend on temperature and process variations

Figure 3-11 is schematic of voltage adder. The voltage adder operation is very simple. The MOSFETs, M1, M2, M3 and M4 change input voltage to current. Converted current is added and copied using M5, M6, M7 and M8. Finally, diode connection MOSFETs, M9 and M10 convert copied current to voltage again. Figure 3-12 is transient simulation result. Two different frequency sinusoidal wave is added well. This is simple voltage adder [13]. But in this proposed equalizer, voltage adder output common mode level stability is very important. Because of stability, common mode feedback is added in normal voltage adder. Figure 3-13 is simulation results of output common mode level. It is tested under process and temperature variations. The worst case is pink line that is under fast p-type MOSFET and slow n-type MOSFET process situation at 150 degree. That value is just 2.525 V. Because of common mode feedback, it is designed that output common mode level is very stable.

3.3.4. Comparing design for Ethernet waveform

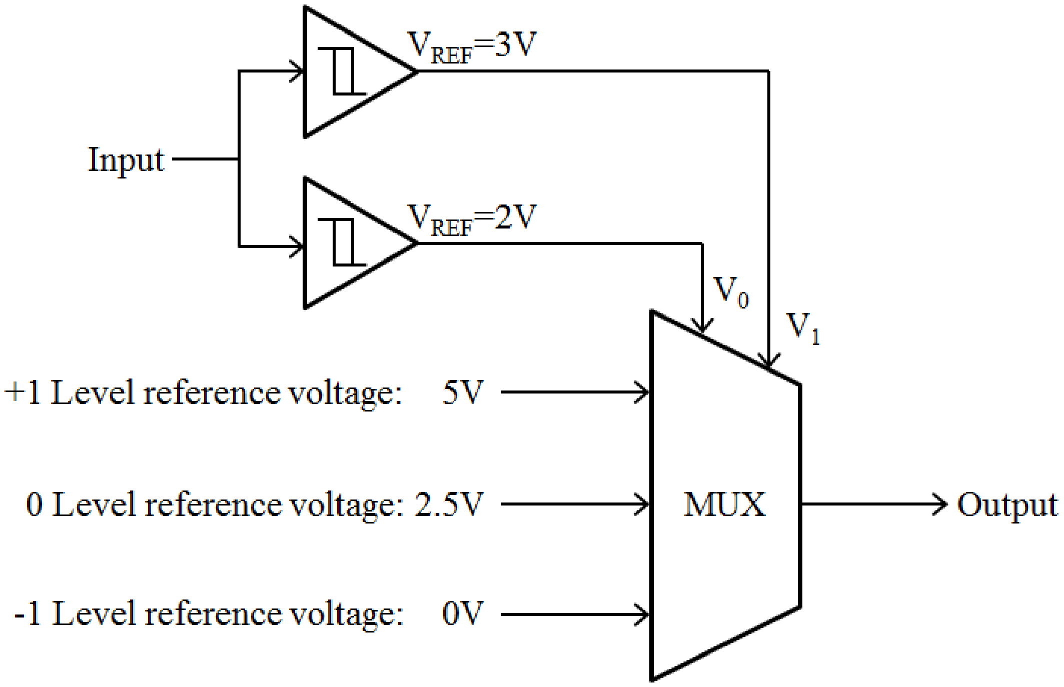

Figure 3-14: Block diagram of MLT-3 comparator in proposed equalizer

	V0	**V1**	**MUX output**
Case 0	1	1	5V
Case 1	1	0	2.5V
Case 2	0	0	0V

Table 3-1: MLT-3 comparator multiplexer in proposed equalizer

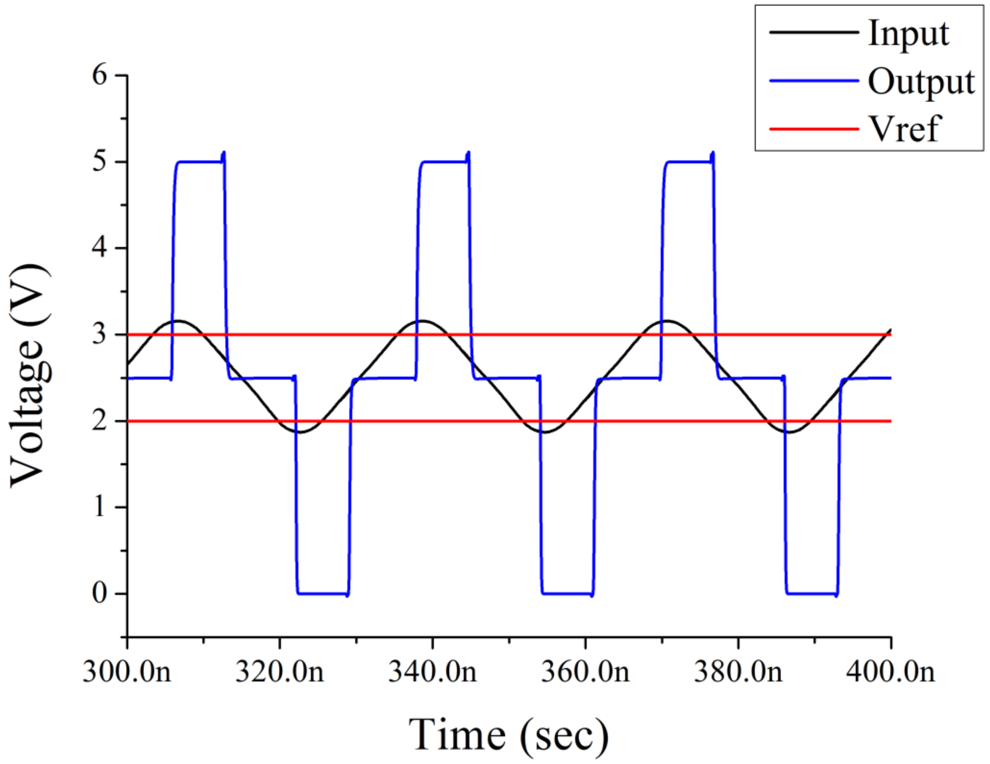

Figure 3-15: Transient simulation results of MLT-3 comparator in proposed equalizer

A comparator is essential block in equalizer. Equalized signal is unclear. A comparator has a reference value and compares with an input signal. The output of comparator has only ‘0’ or ‘1’. MLT-3 comparator also is same with that. However, MLT-3 comparator should have 3 output voltage level, ‘-1’, ‘0’ and ‘1’. Figure 3-15 is block diagram of MLT-3 comparator. MLT-3 comparator has two common comparators. Each common comparator has reference voltage, 2V and 3V. When signal comes to input, two common comparators compare with each reference voltage. The results are ‘0’ (0V) or ‘1’ (5V). After comparing, multiplexer decides the output of MLT-3 comparator. The multiplexer operation is same with a table 3-1. If some signal is 2.8V, it is larger than 2V and smaller than 3V. Comparting result is ‘0’ and ‘1’. As a result, multiplexer output is level ‘0’ (2.5V). This is very simple operation but problem is reference voltages. There are three reference voltages, 2V, 2.5V and 3V. Especially, 2.5V can be unstable because of data transition. When it is designed, reference voltage is shielded using filtering technique.

Chapter 4

Design Results

4.1. Chip fabrication

For fabrication of the proposed automotive temperature compensating Ethernet equalizer, the 0.13um BCDMOS technology provided by Hynix was used. The chip size is 1.2mm x 1.6mm with a pad. Active size of proposed automotive Ethernet equalizer is just 0.5mm x 0.8mm. The supply voltage is 5V.

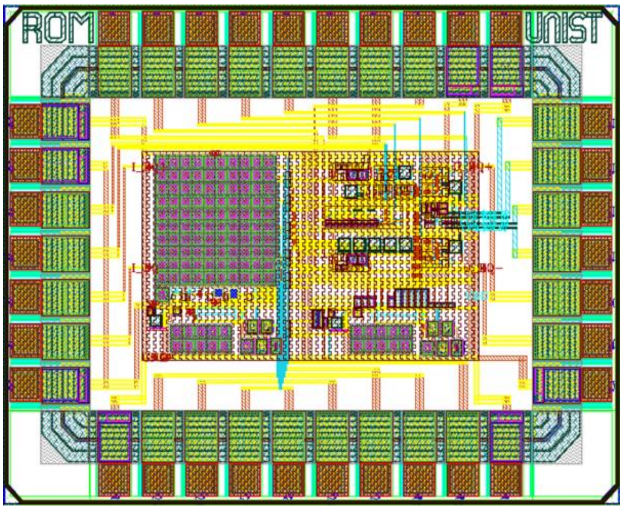

Figure 4-1: Chip of proposed automotive temperature compensating Ethernet equalizer

4.2. Eye diagram of proposed automotive equalizer

Figure 4-2 is eye diagram of proposed equalizer. An eye diagram shows a signal that is repetitively sampled. If eye diagram is opened as wide as an eye, it means signal can be transmitted well. The second one is eye diagram after 100m category-5 cable. Because of channel distortion, the eye diagram after channel is closed totally. However, the eye diagram after proposed equalizer is opened. It means that data is recovered well. And system phase margin is important because this is feedback system. The feedback loop from rectifier to VGA has a 42.74 degree phase margin. For avoiding oscillations safely, it is designed to have a phase margin under 60 degree.

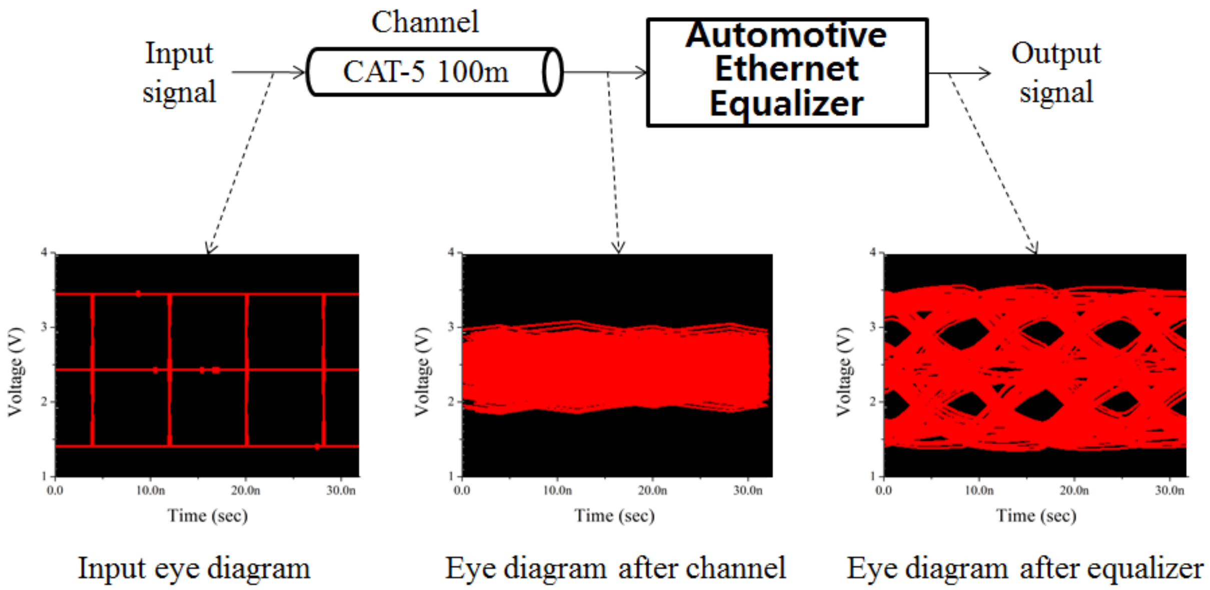

Figure 4-2: Eye diagrams of proposed automotive temperature compensating Ethernet equalizer

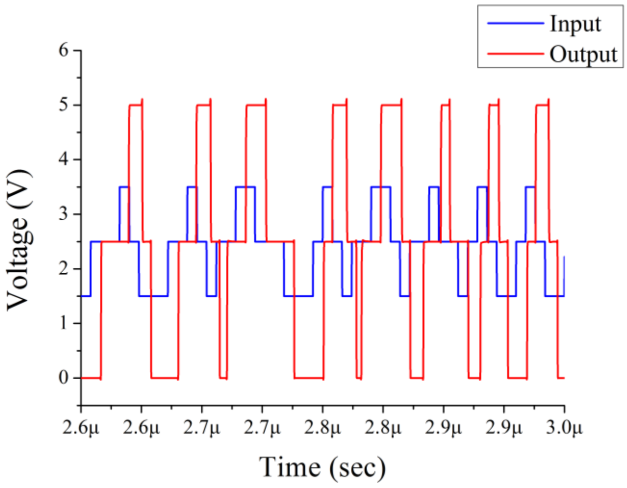

Figure 4-3: Results of non-feedback Ethernet equalizer at 27 degree

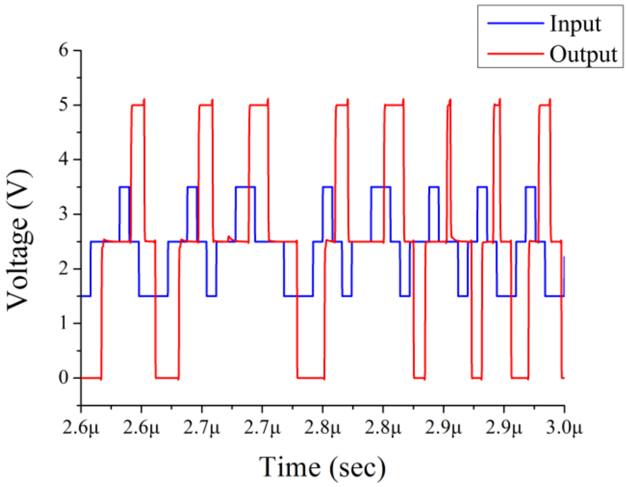

Figure 4-4: Results of non-feedback Ethernet equalizer at 150 degree

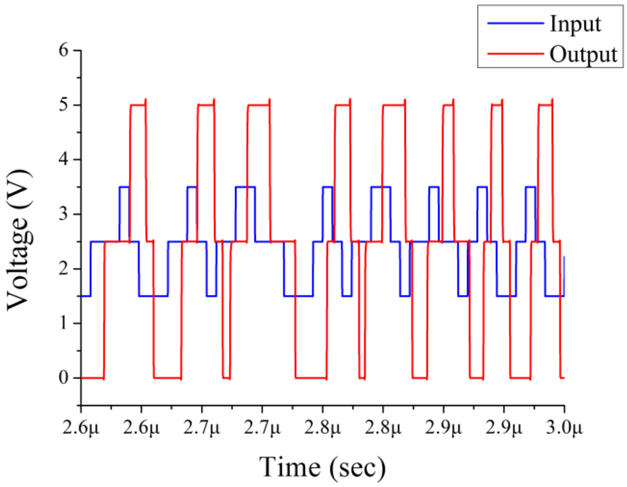

Figure 4-5: Results of proposed automotive Ethernet equalizer at 150 degree

4.3. Results depend on automotive temperature range

This paper proposes the Ethernet equalizer that can compensate automotive temperature range, -40 degree to 150 degree. It should equalize the data at -40 degree to 150 degree. In this part, it is verified that the key function of proposed equalizer compensates a difference depend on automotive temperature range. The figure 4-3 is non-feedback situation at 27 degree. This situation is normal equalizer without compensating temperature function. The blue line is input data and the red line is output of equalizer. Even though without that, the data is recovered well at 27 degree. But in figure 4-4, signal is not recovered. The figure 4-5 is non-feedback situation at 150 degree. There are wrong data transmission at 2.725u sec and 2.825u sec. It also can be wrong data transmission at 2.9u sec. However, if proposed equalizer is used in 150 degree, the signal is equalized well. Figure 4-5 is situation that proposed equalizer is used. The red line is same with the blue line. The output data is totally recovered with the input data. It means that automotive temperature is compensated. As a result, proposed Ethernet equalizer recovers the data at automotive temperature range.

Chapter 5

Future Works

5.1. Discrete-time linear equalizer

In this paper, automotive temperature compensating Ethernet equalizer using continuous-time linear equalizing is proposed. Continuous-time linear equalizer uses a high pass filter. It is designed in frequency domain. It can be made as low power solution. It is also easy to design. However, it has disadvantages. Because of simple concept, continuous-time linear equalizer has low performance. The other type of equalizer is discrete-time linear equalizer. A discrete-time linear equalizer uses a FIR filter. Figure 5-1 is block diagram of discrete-time linear equalizer. Commonly four delay taps are used. Each delayed signal has each amplification factor and that are added. As a result, signal is equalized. A discrete-time linear equalizer consumes high power and has more complexity than continuous-time linear equalizer. However, it has high performance than continuous-time linear equalizer and it is easy to be programmed. Even though it consumes high power, it can be no problem because of automotive applications.

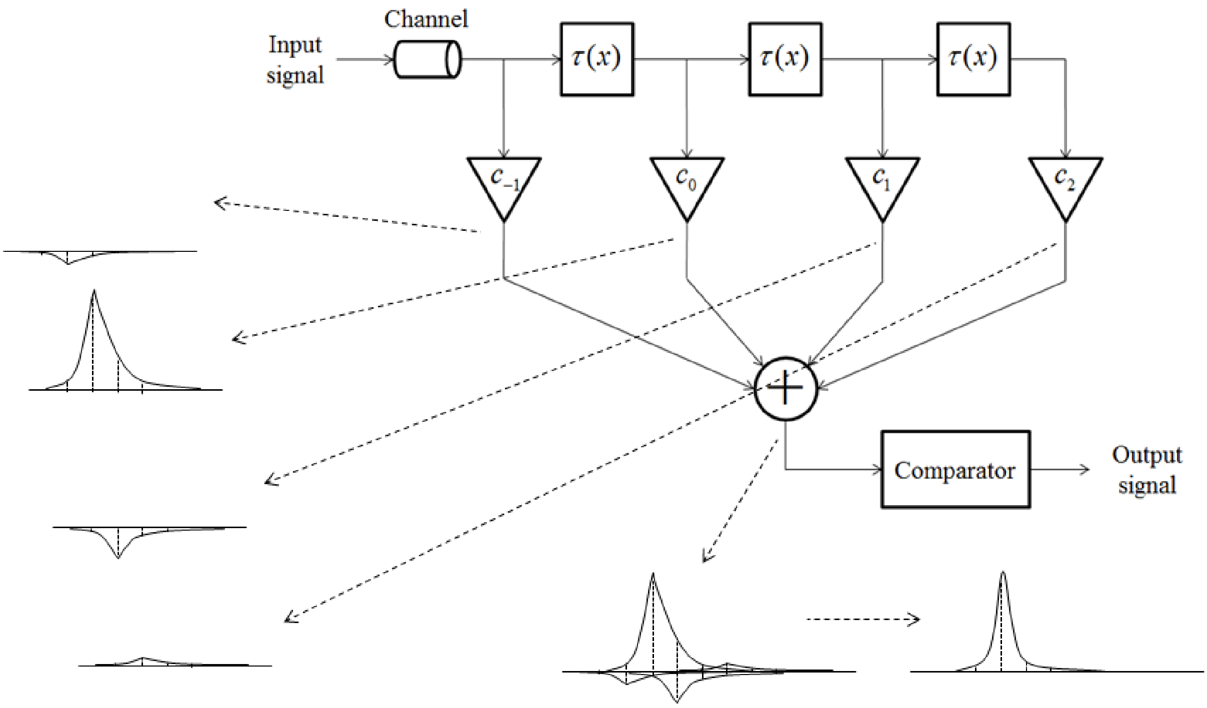

Figure 5-1: Block diagram of discrete-time linear equalizer

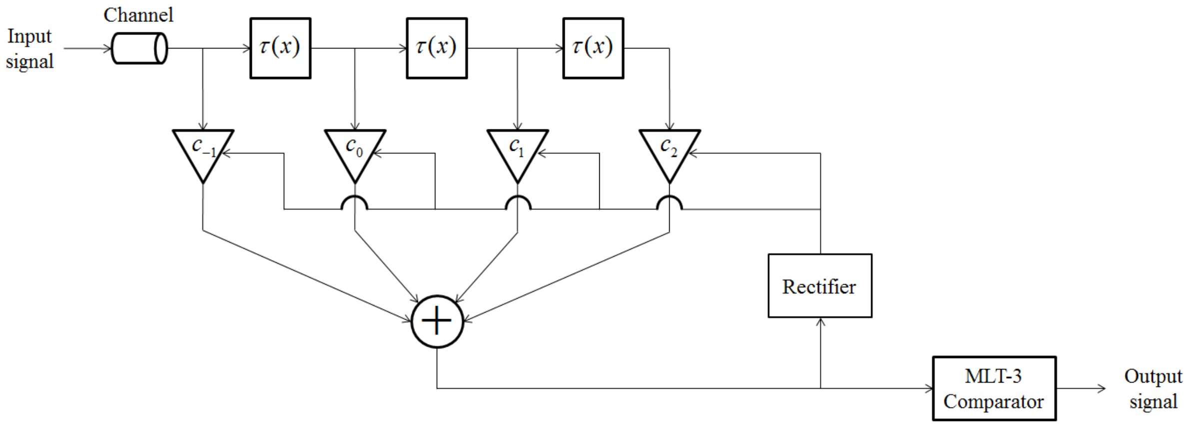

Figure 5-2: Block diagram of next automotive temperature compensating Ethernet equalizer version using discrete-time linear equalizing

5.2. Discrete-time linear type temperature-compensating Ethernet equalizer for automotive applications

Figure 5-2 is discrete-time linear type temperature-compensating Ethernet equalizer for automotive applications. The concept of compensating temperature is similar with a proposed equalizer. The rectifier detects added signal amplitude after voltage adder. If the added signal amplitude is not enough to be compared in MLT-3 comparator because of high temperature, 150 degree, each gain cell make a high gain than before. It is expected to make a wider the eye diagram than proposed one. For implementation of discrete-time linear type temperature compensating Ethernet equalizer, FIR filter should be designed. After design of FIR filter, each block, delay cell and amplifier should be designed. It will be more difficult to implement.

Chapter 6

Summary & Conclusion

In this paper, the Ethernet equalizer that compensates automotive temperature range is presented. The normal communication protocols in automotive are LIN and CAN. However, LIN and CAN have not enough bandwidth to support data communications in the future. More and more, communications in automotive are important because of many electronics in the vehicle. Ethernet protocol can be candidate of automotive communications. It provides 100 Mbps. It is also easy to apply lot of applications because Ethernet is standard in internet and has IP address system. The Ethernet sends the data until 100m cable. In this time, equalizer is essential block that can recover the data in receiver. However it should satisfy AEC-Q100. AEC-Q100 is failure mechanism based stress test qualification for integrated circuits. For meeting AEC-Q100, it should have an operational temperature range from -40 degree to 150 degree. This paper proposes the Ethernet equalizer that can recover the data until 100m CAT-5 cable adaptively at -40 degree to 150 degree. For supporting the wide temperature range, feedback system is used. The proposed equalizer has 31.25 MHz bandwidth and a fully-differential structure. The proposed automotive Ethernet equalizer is implemented in a Hynix 0.13 um BCDMOS technology.

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