

LINT MODULATOR

A Thesis Submitted to the College of
Graduate Studies and Research
in Partial Fulfillment of the Requirements
for the Degree of Master of Science
in the Department of Electrical Engineering
University of Saskatchewan
Saskatoon, Saskatchewan

by

Zhen Ma

Fall 2002

© Copyright Zhen Ma, 2002. All rights reserved.

PERMISSION TO USE

In presenting this thesis in partial fulfilment of the requirements for a Postgraduate degree from the University of Saskatchewan, I agree that the Libraries of this University may make it freely available for inspection. I further agree that permission for copying of this thesis in any manner, in whole or in part, for scholarly purposes may be granted by the professor or professors who supervised my thesis work or, in their absence, by the Head of the Department or the Dean of the College in which my thesis work was done. It is understood that any copying or publication or use of this thesis or parts thereof for financial gain shall not be allowed without my written permission. It is also understood that due recognition shall be given to me and to the University of Saskatchewan in any scholarly use which may be made of any material in my thesis.

Requests for permission to copy or to make other use of material in this thesis in whole or part should be addressed to:

Head of the Department of Electrical Engineering
University of Saskatchewan
Saskatoon, Saskatchewan, Canada
S7N 5A9

ABSTRACT

As the radio spectrum in the lower microwave frequency bands is becoming more crowded, it is almost impossible to support new broadband systems, which use larger portions of the radio spectrum. Thus, new and emerging wireless systems available for broadband services turn towards the high microwave and millimeter-wave spectrum range. Linear modulation schemes like Quadrature Amplitude Modulation (QAM) are preferred in broadband wireless communication systems due to their high spectrum efficiency, which makes them utilize the limited channel bandwidth more efficiently. The problem is that the non-constant envelope of linear modulation schemes requires linear amplification. Linear amplification can be obtained with a Class A amplifier solution, which suffers from very low power efficiency. Poor power efficiency is not suitable for highly integrated or portable equipment, because large batteries are needed to supply extra power, and large transistors and heat sinks are required to dissipate this power. Therefore, a linear modulator architecture that can achieve high power efficiency and implementation at upper microwave and millimeter-wave frequencies is very attractive.

The novel Linear modulation with Nonlinear Translation (LINT) modulator architecture proposed in this thesis is based on the direct modulation method and the Linear amplification with Nonlinear Components (LINC) technique. It involves decomposing arbitrary baseband signals into two constant envelope signals. Then each constant envelope signal is modulated at a subharmonic carrier using vector modulation followed by xN frequency multiplication to achieve frequency translation to the desired output frequency. Highly efficient power amplifiers can be employed to prepare the signal for transmission at a required power level. Finally, two amplified signals are passively combined to produce a high frequency and amplified replica of the input signal. Although frequency multiplication and power amplification are nonlinear processes, the overall input to output transfer function of the LINT modulator is linear. As opposed to the more conventional method of modulation at an IF and upconversion to the desired transmit frequency, the direct modulation method removes the requirement for IF, upconversion, and filtering circuitry, resulting in cost and complexity reduction of the hardware implementation.

The main part of the modulator is a $x12$ two-stage microwave frequency/phase multiplier chain. The multiplier chain consists of $x3$ and $x4$ multipliers connected in cascade, and translates a modulated subharmonic carrier at 2.33 GHz to 28 GHz. The circuitry is simulated assuming soft substrate implementation, which simplifies the fabrication process. The multiplier chain itself shows good performance, and can be used to generate stable source signals at high microwave frequencies.

Performance of the LINT modulator is investigated using realistic multiplier chains. The effect of amplitude imbalance and phase noise on the 16-QAM modulated signal is simulated.

The result of this research presents a generic modulator architecture that is very attractive for broadband wireless applications at upper microwave and millimeter-wave frequencies.

ACKNOWLEDGEMENTS

I would like to express my sincere appreciation and gratitude to my supervisor, Dr. David M. Klymyshyn, for his guidance, support and encouragement throughout this project and the preparation of this thesis. I had great benefit of the graduate level course EE812 (Active Microwave Devices and Circuits) taught by Dr. David M. Klymyshyn.

I would also like to thank the management and staff of Telecommunications Research Laboratories (TRLabs) for providing financial assistance and the use of their facilities during my research. I wish to express my gratitude to Garth Wells and Jack Hanson for their technical assistance.

DEDICATION

To my parents, Zhanjing Ma and Fengrong Wang, and my sister, Liguang Ma.

Contents

PERMISSION TO USE	i
ABSTRACT	ii
ACKNOWLEDGEMENTS	iv
DEDICATION	v
TABLE OF CONTENTS	vi
LIST OF FIGURES	ix
LIST OF TABLES	xii
LIST OF ABBREVIATIONS	xiii
1 INTRODUCTION	1
1.1 Background	1
1.2 Direct Modulation	3
1.3 Linear Modulation	4
1.4 Literature Review	5
1.4.1 Phase Modulation Using Nonlinear Circuits	6
1.4.2 LINC Technology	6
1.5 Research Objectives	7
1.6 Thesis Organization	8
2 DIRECT LINT MODULATION METHOD	9
2.1 Direct LINT Operation	9

2.2	Direct LINT Modulation Architecture	10
2.2.1	Block Diagram of Direct LINT Modulator	10
2.2.2	SCS and Phase Scaler	10
2.2.3	Vector Modulator	13
2.2.4	Frequency/phase Multiplier Chain	15
2.2.5	Power Stage	16
2.2.6	Hybrid Combiner	17
2.3	Summary	18
3	16-QAM MODULATION USING LINT	20
3.1	16-QAM Modulation Scheme	20
3.2	Modulating Signal Design	23
3.3	Effect of Imperfections	30
3.3.1	Amplitude and Phase Imbalance	30
3.3.2	Phase Noise	36
3.4	Summary	38
4	MICROWAVE CIRCUIT DESIGN	39
4.1	Frequency/phase Multiplier	39
4.1.1	Nonlinear Device	39
4.1.2	FET Frequency Multiplier	40
4.2	Harmonic Balance Analysis	45
4.3	Summary	47
5	CIRCUIT REALIZATION	49
5.1	Fabrication Technology	49
5.1.1	Microwave Integrated Circuits	49
5.1.2	Substrate	50
5.2	Transistor Selection	51
5.3	x4 Multiplier Design	52
5.3.1	Basic Design	52

5.3.2	Practical Implementation Considerations	63
5.4	x3 Multiplier Design	67
5.4.1	Basic Design	67
5.4.2	Practical Implementation Considerations	74
5.5	Summary	76
6	SIMULATION RESULTS	77
6.1	Microwave Circuits	77
6.1.1	x4 Multiplier	77
6.1.2	x3 Multiplier	80
6.1.3	Multiplier Chain	83
6.2	Amplitude Imbalance	87
6.3	Phase Noise	90
6.3.1	Basic Circuit	91
6.3.2	Practical Circuit	94
6.4	Summary	94
7	CONCLUSIONS	97
7.1	Summary	97
7.2	Conclusions	98
7.3	Future Work	101
	REFERENCES	102
	APPENDIX	107
A	Data Sheet for NE1280400	107
		111
B	Scaled Layouts for Complete Multipliers	111

List of Figures

1.1	Block diagram of conventional method of digital modulation.	3
2.1	Block diagram of direct LINT modulator	11
2.2	Signal component separation.	13
2.3	Block diagram of vector modulator.	14
3.1	In-phase constellation diagram for 16-QAM.	21
3.2	Quadrature constellation diagram for 16-QAM.	21
3.3	Constellation diagram for 16-QAM.	22
3.4	Block diagram for LINT source signal generation	23
3.5	Gray encoded constellation diagram for 16-QAM.	24
3.6	Frequency response of raised cosine filter.	25
3.7	Impulse response of raised cosine filter.	26
3.8	Eye diagram for 16-QAM with $\alpha = 0.35$	27
3.9	RC filtered vector diagram for 16-QAM	27
3.10	SRRC filtered vector diagram for 16-QAM	28
3.11	Time domain representations of inphase signal at various stages. . .	29
3.12	Trajectory of constant envelope signal after SCS for upper branch. .	31
3.13	Phase of constant envelope signal after SCS for upper branch. . . .	31
3.14	Trajectory of modulating signal for upper branch.	32
3.15	Phase of modulating signal for upper branch.	32
3.16	Spectrum of an oscillator.	36
3.17	SSB phase noise representation.	37
4.1	Simplified circuit of FET frequency multiplier.	41
4.2	Voltage and current waveforms for an ideal x2 FET multiplier . . .	42

4.3	Ideal harmonic drain current components of $I_d(t)$ as a function of duty cycle.	43
4.4	Functional block diagram of a frequency/phase multiplier.	45
5.1	Time waveform of the NE1280400 gate voltage with ideal short circuit drain termination for x4 multiplier.	55
5.2	Layout for simplified x4 multiplier.	57
5.3	Amplitude response of 28 GHz 3rd order coupled line bandpass filter.	59
5.4	Return loss of 28 GHz 3rd order coupled line bandpass filter.	60
5.5	Layout for complete x4 multiplier.	64
5.6	Amplitude response of 28 GHz 2nd order coupled line bandpass filter.	65
5.7	Return loss of 28 GHz 2nd order coupled line bandpass filter.	66
5.8	Time waveform of gate voltage of the NE1280400 with ideal short circuit drain terminations for x3 multiplier.	68
5.9	Layout for simplified x3 multiplier.	70
5.10	Amplitude response of 7 GHz 3rd order coupled line bandpass filter.	71
5.11	Return loss of 7 GHz 3rd order coupled line bandpass filter.	72
5.12	Layout for complete x3 multiplier.	74
6.1	Output power of simplified x4 multiplier.	78
6.2	Harmonic components of simplified x4 multiplier.	78
6.3	Output power of complete x4 multiplier.	79
6.4	Harmonic components of complete x4 multiplier.	80
6.5	Output power of simplified x3 multiplier.	81
6.6	Harmonic components of simplified x3 multiplier.	81
6.7	Output power of complete x3 multiplier.	82
6.8	Harmonic components of complete x3 multiplier.	83
6.9	Output power of simplified x12 multiplier chain.	84
6.10	Harmonic components of simplified x12 multiplier chain.	85
6.11	Output power of complete x12 multiplier chain.	86
6.12	Harmonic components of complete x12 multiplier chain.	86

6.13 Combined constellation diagram for 16-QAM with ± 0.1 dB (inside four points) and ± 0.2 dB (outside four points) input imbalance using simplified multiplier chains.	87
6.14 Combined constellation diagram for 16-QAM with ± 0.1 dB (inside four points) and ± 0.2 dB (outside four points) input imbalance using complete multiplier chains.	88
6.15 Input output relationship for simplified multiplier chain.	89
6.16 Input output relationship for complete multiplier chain.	90
6.17 SSB phase noise of simulated 2.33 GHz oscillator for circuitry using simplified multiplier chains.	92
6.18 Effect of phase noise on combined 16-QAM signal using simplified multiplier chains.	93
6.19 SSB phase noise of simulated 2.33 GHz oscillator for circuitry using complete multiplier chains.	95
6.20 Effect of phase noise on combined 16-QAM signal using complete multiplier chains.	95
B.1 4:1 Scaled layout for complete x4 multiplier	112
B.2 3:1 Scaled layout for complete x3 multiplier	113

List of Tables

3.1	Relationship between amplitude level and Gray code.	24
5.1	Harmonic drain current components for NE1280400 with ideal short circuit drain terminations for x4 multiplier.	56
5.2	Calculation results for 3rd order Butterworth coupled line filter. . .	58
5.3	Voltage reflection coefficients of the output bias circuitry and output termination circuitry for simplified x4 multiplier.	61
5.4	Harmonic drain current and voltage components for NE1280400 with output termination circuitry for simplified x4 multiplier.	61
5.5	Calculation results for 2nd order Butterworth coupled line filter. .	64
5.6	Voltage reflection coefficients of the output bias circuitry and output termination circuitry for complete x4 multiplier.	66
5.7	Harmonic drain current components for NE1280400 with ideal short circuit drain terminations for x3 multiplier.	68
5.8	Voltage reflection coefficients of the output drain termination circuitry for simplified x3 multiplier.	72
5.9	Harmonic drain current and voltage components for NE1280400 with output termination circuitry for simplified x3 multiplier.	73
5.10	Voltage reflection coefficients of the output drain termination circuitry for complete x3 multiplier.	75
6.1	SSB phase noise of a typical oscillator.	93

LIST OF ABBREVIATIONS

ACI	adjacent channel interference
ADS	Advanced Design System
ASK	Amplitude Shift Keying
ATC	American Technical Ceramics
ATM	asynchronous transfer mode
b/s	bits per second
BPF	bandpass filter
bps/Hz	bit per second per Hertz
CW	continuous wave
dB	decibel
dBc	decibels relative to carrier
dBc/Hz	decibels relative to carrier per Hertz
dBm	decibels relative to 1 milliwatt
DC	direct current
DSP	digital signal processing
FET	field effect transistor
FPGA	field programmable gate array
FSK	Frequency Shift Keying
GHz	gigahertz
GMSK	Gaussian Minimum Shift Keying
Hz	hertz
<i>I</i>	in-phase
IEEE	Institute of Electrical and Electronics Engineers, Inc.
IF	intermediate frequency
IMD	intermodulation distortion

ISI	intersymbol interference
KCL	Kirchoff's Current Law
kHz	kilohertz
LINC	LInear amplification with Nonlinear Components
LINT	LInear modulation with Nonlinear Translation
LMDS	local multipoint distribution service
mA	milliamp
Mbits/s	mega bits per second
MIC	microwave integrated circuit
mil.	0.001 inches
MMDS	multichannel multipoint distribution service
MMIC	monolithic microwave integrated circuit
mS	millisiemens
MSK	Minimum Shift Keying
Ω	Ohms
OFDM	orthogonal frequency division multiplexing
pF	picofarads
PSK	Phase Shift Keying
PTFE	polytetrafluorethylene
Q	quadrature
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RC	raised cosine
RF	radio frequency
rms	root mean square
SCS	signal component separator
SRD	step recovery diode
SRRC	square root raised cosine
SSB	Single Sideband
sym/s	symbols per second

μ s	microseconds
V	volt
WLAN	wireless local area network

Chapter 1

INTRODUCTION

1.1 Background

Wireless communication grew enormously in the last decade, and it shows little sign of slowing. It was predicted that wireless would surpass wireline as the dominant method of telecommunications worldwide by 2008 [1]. In addition to expanded voice services, the driver for wireless growth will be the demand for high-speed data and video services, using high speed transport techniques like asynchronous transfer mode (ATM) at rates of 155 and 622 Mbits/s [2]. As high-speed data transportation occupies a large bandwidth, the demand for broadband wireless (communication techniques that use larger, or broader portions of radio frequency spectrum) will increase substantially.

However, the radio spectrum in the lower frequency bands is becoming more and more crowded, which makes it almost impossible to support new broadband systems. Thus new and emerging wireless systems available for broadband services are moving towards high microwave and millimeter-wave frequency bands.

Wireless local area networks (WLANs) are examples of broadband technology, which provides high bandwidth to users in a limited geographical area like factories, warehouses and offices. The IEEE 802.11 standard [3] developed within the Institute of Electrical and Electronics Engineers, Inc. (IEEE) is a popular and successful standard for WLAN. In the 1999 edition of IEEE 802.11 standard, a maximum data rate of 2 Mbits/s in the 2.4 GHz band is supported. In IEEE 802.11b, which is one of the two additional amendments for 802.11, much higher data rates up to 11 Mbits/s are provided at the same frequency band. In the 802.11a amendment, data

rates up to 54 Mbits/s are provided using orthogonal frequency division multiplexing (OFDM) technique in the 5-6 GHz bands.

In order to provide higher bit rates, an ATM-based millimeter-wave WLAN for application in the 60 GHz frequency band was developed [4]. This ATM-based WLAN has a target data rate of 155 Mbits/s due to the greater bandwidth available in millimeter-wave frequency band. It is expected to be commercially available in the near future. Another system that can provide broadband services is called multichannel multipoint distribution service (MMDS). MMDS is a bi-directional, high-speed fixed broadband wireless networking service operating in the 2 to 3 GHz range. It supports data rates up to 37 Mbits/s. Unfortunately, due to the lack of frequencies in lower microwave portion of spectrum, MMDS is viable only in a limited number of countries [5]. Another emerging broadband wireless technology that has much stronger market potential than MMDS is local multipoint distribution service (LMDS). LMDS, like MMDS, is a high-speed bi-directional wireless networking service, but operates at much higher frequencies - typically in the 28, 38 or 40 GHz bands [5] [6]. There is high bandwidth available for LMDS in most, if not all, countries. This allows data delivery at speeds up to 155 Mbits/s - over four times that of MMDS systems.

Although it is becoming increasingly apparent that millimeter-wave spectrum range must be utilized in order to provide wireless communications with high bit rates, the technology of transceiver design in such frequency is not quite mature. Simple, high performance and cost-effective transmitter operating at millimeter-wave frequency bands is very attractive for the future development of wireless broadband communications.

As these emerging systems are commercialized, high performance modulator architectures which result in cost-effective hardware realizations will become increasingly attractive.

1.2 Direct Modulation

Modulation is a signal processing technique in which one signal (the modulating signal) modifies a property of another signal (the carrier signal) so that a composite signal (the modulated signal) is formed. In digital communication systems, the modulating signal is a sequence of discrete messages. This signal is used to modify the amplitude, phase or frequency of a sinusoidal carrier signal. The conventional method of digital modulation is performed at an intermediate frequency (IF), then the signal is upconverted to the desired transmitting frequency using several mixers, oscillators, and bandpass filters (BPF) as shown in Figure 1.1. While this method yields good performance, it is expensive since it results in substantial hardware.

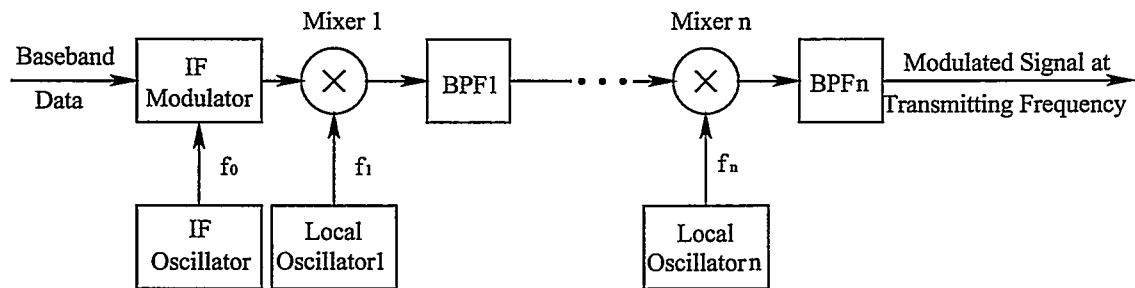


Figure 1.1 Block diagram of conventional method of digital modulation.

As an alternative, direct modulation is an attractive option for reducing the cost and complexity of the transmitter. With this method, the amplitude, phase, or frequency of a sinusoidal carrier is modulated at the transmitting frequency directly by the baseband information sequence. Direct modulation removes the requirement for multiple stages of IF, upconversion and filtering circuitry. If the carrier produced by a single microwave power oscillator is directly modulated at the desired transmitting power level, the requirement for a high power amplifier as the final stage in the transmitter is also removed. The result is a significant reduction in the hardware required in the transmitter.

1.3 Linear Modulation

Most wireless communication systems use digital modulation techniques to transmit data on a carrier signal. There are three characteristics that can be changed with time: amplitude, phase and frequency. The result forms three major categories of modulation techniques currently employed in modern communication systems: Amplitude Shift Keying (ASK), Phase Shift Keying (PSK), and Frequency Shift Keying (FSK). Among them, the amplitude modulation technique, in which the amplitude of the modulation envelope is directly proportional to the amplitude of the data signal at all modulation frequencies, is sometimes called linear modulation. Constant envelope modulation schemes, such as frequency and phase modulations, are examples of nonlinear modulation.

The goal of modulation is not only to effectively transport the message signal through a radio channel, but also to achieve this with desirable qualities, such as high power efficiency and high bandwidth efficiency or spectral efficiency.

The massive growth in wireless has put great strain on scarce spectral resources, resulting in overcrowded communication channels. In this regard, it is very important that each communication uses as little bandwidth as possible. Thus, the modulation technique that enables more information to be carried over a limited channel bandwidth is preferred. Bandwidth efficiency is the term that describes how efficiently the allocated bandwidth is utilized by a modulation scheme. Bandwidth efficiency, η , is defined as the transmitted bit rate divided by the bandwidth of the signal, which can be expressed mathematically as [7]

$$\eta = \frac{R_b}{W}, \quad (1.1)$$

where W is the bandwidth of modulated signal in Hz, and R_b is the bit rate in b/s.

Bandwidth efficiency improves as more information bits are sent with each modulating "symbol". The symbol rate, R_s , is the bit rate divided by the number of bits that can be transmitted with each symbol. Theoretically, the minimum occupied bandwidth of the modulated signal is equal to the symbol rate. Substituting

for bandwidth, W , in Equation 1.1 with the symbol rate, the theoretical maximum bandwidth efficiency is equal to the number of bits transmitted with each symbol.

Nonlinear modulation formats like FSK and Minimum Shift Keying (MSK) have low bandwidth efficiency on the order of 1 bps/Hz. Linear modulation formats can achieve much higher bandwidth efficiency, thus make more efficient use of the spectrum. For example, the theoretical bandwidth efficiency of Quadrature Phase Shift Keying (QPSK) modulation format is 2 bps/Hz, and 16-QAM is 4 bps/Hz. The superior spectral efficiency characteristic of high order linear modulation schemes makes them desirable in wireless communication applications. In the proposal for the IEEE 802.16 standard on broadband wireless access, QAM is recommended as the modulation format due to the high spectral efficiency [8].

Although highly spectrally efficient, high order linear modulations have poor power efficiency. With the varying envelope, linear modulation schemes are especially sensitive to nonlinear amplification and require highly linear, low efficient amplifiers, which reduces the desirability of implementing such modulation formats in many applications. This is the reason that the less bandwidth efficient constant amplitude modulation formats like MSK are still popular in mobile communication systems, where power efficiency is extremely important. A simple architecture for power efficient linear modulation at high frequencies would be very attractive for emerging applications.

1.4 Literature Review

As discussed in Section 1.3, linear modulation methods are desirable in wireless communication system because with these methods, limited spectral resources can be effectively utilized. However, the amplitude variations of the carrier signals require linear amplification, which suffers from very low power efficiency. Therefore, it is attractive to develop a method, with which both high spectral efficiency and high power efficiency can be obtained.

1.4.1 Phase Modulation Using Nonlinear Circuits

A simple Gaussian Minimum Shift Keying (GMSK) modulator architecture operating at upper microwave frequency band has been reported [9]. This modulator employs direct modulation, resulting in reduction of the cost and complexity of the hardware architecture. The modulator is based on achieving continuous linear phase modulation of a carrier signal over the full 360° range. The 360° phase shifter is realized by using a highly linear fractional-range phase shifter and a frequency/phase multiplier. The xN frequency/phase multiplier expands the fractional phase shift range by a factor xN to full 360° , and upconverts a subharmonic input frequency by xN to 18 GHz. High power efficiency can be obtained by using an efficient Class C amplifier at the output, as GMSK is a constant envelope modulation format. The transmitted frequency can be easily extended to higher frequency range just by increasing the multiplication factor of the frequency/phase multiplier.

Although this modulator architecture is simple, and works well for generating constant envelope continuous phase modulations with high power efficiency, it can not reliably produce linear amplitude modulation and is not applicable to spectrally efficient linear modulation schemes.

1.4.2 LINC Technology

LINC technique is one of the most promising methods for obtaining linear amplification with high power efficiency. The concept is derived from the outphasing modulation technique developed in the 1930s [10]. In 1974, it was introduced as the LINC technique [11]. The concept involves decomposing any input signal into two phase modulated, but constant envelope, signals. Then the constant envelope signals are amplified through power efficient but nonlinear amplifiers separately, and finally passively combined to produce an amplified replica of the input signal. Although nonlinear components are contained in the LINC amplifier, the overall input to output transfer function of the LINC amplifier is linear [11].

The LINC concept has been developed further in various papers since it was introduced. Component signal separation and recombination was examined in [12];

a practical prototype LINC transmitter operating at 170 MHz was constructed and tested in [13]; the effect of imbalances and modulation schemes on performance of LINC transmitters was presented in [14], [15] and [16]; the effect of quantization for LINC transmitters was analyzed in [17]; a signal combiner implementation to achieve high efficiency was described in [18]; techniques for correcting the imbalances in LINC transmitter is studied in [19], [20], [21] and [22].

With the LINC architecture, both high power efficiency and spectral efficiency can be obtained. One disadvantage of this technique is that it is not suitable for implementation at upper microwave and millimeter-wave frequency bands, as it is difficult to accomplish a stable reference signal and precise vector modulation at such high frequencies.

From the literature review, it is apparent that little research has been reported on extending the direct modulation and LINC concept to linear modulation methods suitable for implementation at upper microwave and millimeter-wave frequencies. A modulator that combines direct modulation with LINC technique has advantages of simple structure, power and spectral efficiency and suitability for linear modulation schemes. If nonlinear concepts for providing frequency translation similar to those described in Section 1.4.1 were also exploited, the hardware complexity could be substantially reduced and the result would be a very attractive architecture for applications at upper microwave and millimeter-wave frequencies.

1.5 Research Objectives

This thesis focuses on developing a simple, generic linear modulator suitable for a wide range of transceiver functions required in emerging wireless communication systems operating at upper microwave and millimeter-wave frequencies. The new modulator is named LINT, an acronym for LInear modulation with Nonlinear Translation, which attempts to incorporate the desirable features of frequency translation and power efficiency into linear modulation at high frequencies. The main objectives of the research are summarized as follows:

1. Propose a new modulator architecture (LINT), which is suitable for linear

modulation schemes at microwave and millimeter-wave frequencies with high power efficiency and frequency translation.

2. Investigate the validity of LINT signal component separation and phase scale algorithm.

3. Design and simulate realistic microwave circuits for evaluation of the LINT technique.

4. Investigate the performance of the LINT technique with typical modulator impairments such as amplitude imbalance and phase noise.

1.6 Thesis Organization

This thesis is organized into seven chapters. In Chapter 2, the direct LINT modulation method is presented. The architecture of the LINT modulator is described in detail.

In Chapter 3, LINT modulating signal design and imperfections in the LINT technique that will affect the overall performance of LINT modulator is discussed. Simulation results using MATLAB for the modulating signal design are presented.

In Chapter 4, theoretical and practical considerations in FET frequency/phase multiplier design at microwave frequencies are described.

In Chapter 5, considerations for microwave circuit realization are discussed. The design procedures for simplified microwave circuits and complete microwave circuits suitable for MIC fabrication are presented.

In Chapter 6, simulation results for the simplified and complete circuits designed in Chapter 5 are presented. Two imperfections that will degrade the overall performance of LINT modulator are also simulated in this chapter.

In Chapter 7, conclusions of this research are presented and future research directives are suggested.

Chapter 2

DIRECT LINT MODULATION METHOD

2.1' Direct LINT Operation

The principle of the LINT modulator is to decompose arbitrary baseband non-constant envelope source signals into alternative baseband modulating signals used to produce two constant amplitude phase modulated signals. These two signals are then frequency translated to the desired transmitting frequency separately with two identical paths of frequency/phase multiplier chains. An efficient power amplifier operating at this high transmitting frequency in each path delivers two branches of signals at the desired transmitting power level. Finally these two high frequency and high power signals are passively recombined with a hybrid combiner. Although frequency/phase multiplier chains and power amplifiers are highly nonlinear circuits, no intermodulation distortion (IMD) will be introduced due to the constant envelope property of the input signals. In this respect, the overall direct LINT modulator is insensitive to the nonlinear characteristic of the circuits in its structure. Thus, the output signal from the modulator is a frequency translated and amplified replica of the source signal. Also high power efficiency can be obtained from this modulator since highly efficient power amplifiers are employed. The linear property of this direct LINT modulator makes it suitable for a variety of linear modulation schemes like QAM, which have a higher bandwidth efficiency than constant envelope frequency modulations. The direct LINT modulator architecture is presented in the next section.

2.2 Direct LINT Modulation Architecture

In this section the block diagram of direct LINT modulator is presented. The theoretical principle of each functional block for the modulator is described in depth.

2.2.1 Block Diagram of Direct LINT Modulator

The block diagram of the direct LINT modulator is shown in Figure 2.1. The basic principle is that the baseband source signal, $s(t)$, is separated into two constant amplitude but phase modulated signals in what is called the signal component separator (SCS) and phase scaler. The baseband constant amplitude signals are then further decomposed into in-phase (I) and quadrature (Q) components, which drive vector modulators to modulate subharmonic carrier signals. Then the two modulated signals at the subharmonic are frequency translated to the desired transmitting frequency in two identical $\times N$ frequency/phase multiplier chains. After frequency translation, the two path signals are amplified through power amplifiers and then passively recombined to produce a bandpass replica of the original input source signal. More details of the direct LINT modulator architecture are described next.

2.2.2 SCS and Phase Scaler

The principle of the SCS is similar to the signal separation method of the LINC transmitter [14], but also requires a phase scaler.

A general baseband representation of the bandlimited modulating signal can be written as

$$s(t) = r(t)e^{j\phi(t)}; 0 < r(t) < r_{max} \quad (2.1)$$

where $r(t)$ is the amplitude of the baseband signal, and $\phi(t)$ is the phase of the baseband signal, and represents the desired amplitude and phase modulation of the carrier signal. This signal can be split into two signals, $s_{i1}(t)$ and $s_{i2}(t)$, by adding and subtracting a perpendicular vector from $s(t)$ as shown in Figure 2.2. Hence

$$s_{i1}(t) = s(t) + e(t), \quad (2.2)$$

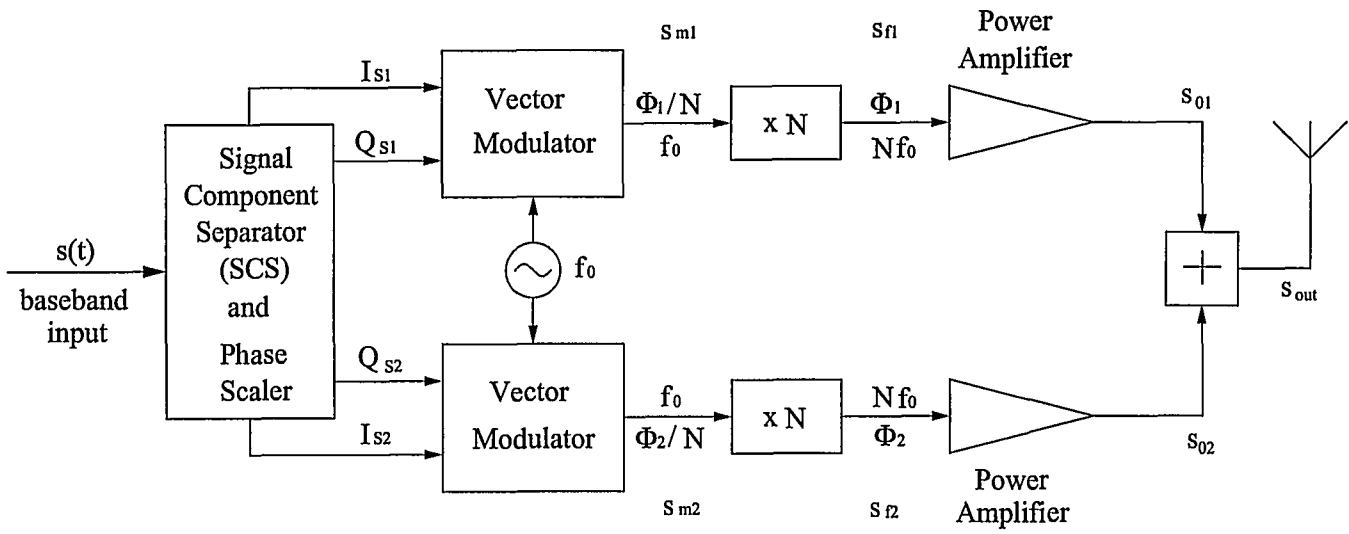


Figure 2.1 Block diagram of direct LINC modulator .