Vector modulators for adaptive and multi-function microwave communication systems

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Abstract
A comprehensive review of microwave serendipity modulators and vector modulators is presented. The vector control and small-shift frequency translation functions of microwave vector modulators, as well as possible multi-function solutions, are discussed. New applications for the vector modulator are proposed for adaptive multiple access communication systems. It is believed that such techniques can be used to achieve high levels of performance, while minimising hardware complexity and costs, for future communication system applications.

Introduction
There are two generic types of microwave vector modulator. The first is the common I-Q type of vector modulator [1-6]. The second type of vector modulator simply consists of an attenuator in cascade with a phase shifter [7-10]. This latter implementation does not have the inherent SIR insertion loss penalty of the former type. Also, the levels of AM/PM conversion and PM/AM conversion of the attenuator and phase shifter, respectively, can be calibrated out by the other. A great deal of work has been reported on the design of high performance digital attenuators [11] and phase shifters [12]. However, when compared to a purely digital implementation, analogue control devices have the following advantages to offer, they:
• require only one control wire per device
• do not require expensive loudness processing to realise high quality switches
• require almost no control power with a passive reflection topology incorporating varactor diodes and ‘cold-FETs’
• can make much more efficient use of expensive chip space with a reflection topology that uses active circulators [6]
• do not suffer from quantization errors
• easily correct for any degradation in performance attributed to fabrication process variations
• enable calibration corrections to be performed once integrated into a subsystem
• easily correct for any degradation in performance attributed to fabrication process variations
• are free from clock-related spurious harmonics

As a result, there is now growing interest in analogue control devices — since they are ideal for use in completely adaptive applications. To this end, the Communications Research Group at King's College has been working on wideband analogue attenuators, phase shifters, and delay lines for over four years [13-17]. Two important functions that can be performed by a microwave vector modulator are vector control and small-shift frequency translation.

Vector Control
The use of the vector control function can be found in the following communication systems applications:-
• T/R modules in phased array antennas [2,6,10]; multipath fading microwave emulators [7]; high power amplifier linearisers [1,9]; and direct PSK/QAM modulators [3,4]. With the latter homodyne digital modulation technique there are no IF stages — modulation by the baseband signal is performed directly at carrier frequency. This technique offers the advantage of simplicity, over the more conventional heterodyne techniques. Also, baseband filtering may be employed, for spectral sidelobe suppression, in preference to the less power efficient and more expensive method of using high-Q microwave filters. In addition, it is proposed here that a direct sequence (DS) spread spectrum (SS) code division multiple access (CDMA) modulator can also be implemented as a simple extension of direct PSK modulation.

Frequency Translation
Small-shift frequency translations are traditionally required in modern microwave measurement and radar systems. Examples include:- homodyne vector network analysers [18]; frequency scanning antennas; and velocity detection ECM systems [19]. However, there are possible applications for such frequency translations in microwave communication systems.
A large-shift frequency translator, employing a conventional mixer, usually requires an output filter. As the required frequency translation is reduced, the Q-factor of the filter must increase, in order to adequately attenuate the unwanted unwanted sidebands generated by the inefficient mixing process. A point is reached when the frequency translation is equal to the bandwidth of the signal to be translated. At this point, only a theoretical 'brick-wall' filter could be considered. Beyond this point, there will be inherent distortion due to spectral overlap.
In practice, small frequency translations can only be performed using either a non-mixing sinusoidal
modulator or a serrodyne modulator. With both techniques, the generation of significant unwanted sidebands can be avoided — therefore, improving RF power efficiency and removing the need for an unrealisable filter. In addition, the unwanted sideband suppression is not normally a function of the input RF power level.

The sinusoidal modulator simply introduces a continuously linear change, with time, in its insertion phase. An increasing change causes a positive frequency translation, by an amount that is proportional to the rate of change. Conversely, a decreasing change causes a negative frequency translation. Non-linear sinusoidal modulators have been realised using a mechanically rotating dielectric slab, rotating magnetic field, balanced diode modulators and I-Q vector modulator. The first two examples are not compatible with microwave integrated circuit technology and the last three examples require quadrature sinusoidal control signals - making a complete MMC frequency translator difficult to realise with the last two examples.

The serrodyne modulator is a derivative of the sinusoidal modulator. Here, a klystron, TWT or phase shifter is modulated with a sawtooth waveform, such that one period of the sawtooth results in an induced phase shift that linearly sweeps through an integer multiple of 360°. For a 360° phase shifter, the amount of frequency translation is equal to the repetition rate of an ideal sawtooth waveform, as illustrated in Figure 1. The direction of frequency translation can be changed by simply inverting the sawtooth profile.

It must be noted that conversion loss can be defined in one of two ways. Firstly, conversion loss is the difference in power levels between the output signals at the input frequency (with no modulation applied) and the output frequency (with modulation applied). Secondly, conversion loss is the difference in power between the input signal and the output signal. The former definition is traditionally applied to both types of small-shift frequency translator. As a result, they can have an inherent conversion loss of 0dB. The latter definition is traditionally applied to the mixer type of large-shift frequency translator. In this case, the small-shift frequency translator would ideally have a conversion loss equal to its insertion loss.

Prior to 1970, serendipity modulators received a great deal of attention [20]. However, in the past two and a half decades, very little has been published on this subject, perhaps because of the increasing popularity of the I-Q vector modulator. The Communications Research Group has played a significant role in the recent revival of the serrodyne modulator.

Serrodyne modulators have traditionally employed digital phase shifters in preference to analogue phase shifters. One reason for this is that high performance analogue phase shifters have not been readily available in recent years. Two analogue serrodyne modulators have previously been demonstrated, employing cascaded-match reflection-type phase shifters (CMRTPS) [13-15] to overcome the problem of narrow bandwidth. The CMRTPS topology enables a high performance, low cost, wide frequency range and at all levels of relative phase shift. This characteristic is important if wide RF bandwidths are to be translated and/or the serrodyne modulator is to cover a wide frequency range.

A 14 GHz serrodyne modulator was first reported [21]. Here, both analogue and DSP control signals were used to correct for the nonlinear tuning characteristic of the phase shifter. The measured performance for the serrodyne modulator is shown in Figure 2. It is believed that this was the first analogue serrodyne modulator to employ a nonlinear 360° phase shifter and the first to be realised using monolithic technology. A 24 GHz serrodyne modulator was later demonstrated using a coplanar waveguide MMIC phase shifter [22]. It is believed that this was the first single-chip 360° analogue phase shifter to be realised using coplanar waveguide technology.

The measured performances demonstrated by both MMIC serrodyne modulators could be greatly improved if a variable attenuator was employed to compensate for the non-ideal PM/AM conversion characteristics of the phase shifters. The small-shift frequency translation function of the resulting vector modulator could then be used to meet the demanding specifications required by future high performance adaptive communication systems, including fast-frequency hopping (FFH) CDMA modulators and frequency-division multiplexers.

FFH CDMA Modulator:

Fast frequency hopping in CDMA communication systems can be easily performed with small-shift frequency translators, as illustrated in Figure 3. In both the frequency hopping transmitter and receiver, the translator removes the need for an elaborate frequency synthesiser/band pass filter arrangement, thus, saving power on complexity and cost. Also, since very smooth phase transitions are possible with vector modulators, the levels of undesirable spurious signals that are sometimes generated by frequency synthesizers can be avoided.

Heterodyne Frequency Division Multiplexer:

Frequency division multiplexing is also an ideal application for small-shift frequency translators, as illustrated in Figure 4. In both the implementation of frequency translators, N channels or N groups of channels can be frequency multiplexed without the need for N highly stable carrier generators or a frequency synthesizer. The proposed solution provides a high degree of modularity, since only the low frequency signal generators (within the frequency translators) are different, offering low complexity and low cost. A frequency division demultiplexer can be realised in a similar way to the multiplexer.

Multi-Function

Homodyne SCPC FDMA Modulator:

Because of the inherent multi-functional nature of the microwave vector modulator, it is possible to perform digital modulation, frequency translation and spectral shaping — all within a single microwave component under DSP control. Novel examples of multi-function applications include slow frequency hopping DS/SS CDMA modulators and frequency division multiple
access (FDMA) modulators. The discrete architecture and novel integrated multi-function solution for a demand-assigned single carrier per channel (SCPC) FDMA modulator are illustrated in Figure 5. It can be seen that in the discrete case there is an unnecessary duplication of elements in the vector controller and frequency translator.

Conclusions

A comprehensive review of microwave serendipity modulators and vector modulators has been presented. The vector control and small-shift frequency translation functions of microwave vector modulators, as well as possible multi-function solutions, have been briefly discussed and new applications have been proposed for adaptive multiple access communication systems. It’s believed that microwave vector modulators can be used to achieve high levels of performance, while minimising hardware complexity and costs.

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References

Figure 1. Illustration of the Serrodyne Modulator

Figure 2. Measured Performance of a Serrodyne Modulator

Figure 3. Fast Frequency Hopping CDMA Architecture

Figure 4. Frequency Division Multiplexer Architecture

Figure 5. Architectures For a SCPC FDMA System