# RF Modems — Part I

*Part I provides an introduction to the subject of RF modems and covers designs for single channel units.*

*By John Hatchett and Bill Howell*
*Motorola Semiconductor Products Sector*
*Phoenix, AZ*

RF modems provide a means of relaying digital data between two locations by modulating/demodulating a rrier signal. In this sense they are like ..ore common modems that interface to telephone networks. For telephone line modems, however, the carrier signal frequency lies within the audio range (<3 kHz) while for RF modems the carrier signal falls in the RF spectrum and is typically transmitted via the airways or a broadband coaxial cable similar to that used in CATV networks. RF modem carrier frequencies to over 400 MHz are practical for cable systems and operation to over 100 MHz is quite common. RF modems offer high data rates and the simultaneous use of many channels (one per RF carrier employed) and are frequently used in distribution systems and CATV networks.

The maximum data rate and number of operating channels required of an RF modem varies with the application. In some cases a single channel (or a transmit/receive channel pair) is sufficient. In other applications a multi-channel modem is required. The term "frequency agile" is used to describe modems that can be programmed to operate on various channels or carrier frequencies. In addition to being a key cost determining factor, the data rate also establishes bandwidth requirements for each RF channel d thus sets the maximum number of channels possible within a given system bandwidth. For example, 6 MHz of system bandwidth might be used to accommodate approximately 20 to 60 low data rate (64 Kbit) channels or two high data rate (approximately 1.5 to 2.5 Mbit) channels.

## The Basics

The major functions of a frequency agile RF modem and its associated digital interface are given in Figure 1 along with ICs (also see Inset) useful for their implementation. The digital interface provides the necessary system control and data processing but is normally not considered as part of the RF modem itself.

The modem in Figure 1 can be programmed to operate on one of many RF channels via the channel code provided to the channel control function. This is accomplished by making the channel control function a phase-locked-loop (PLL) RF frequency synthesizer. A synthesizer controls both the transmitter's RF output signal frequency and the receiver's local oscillator or mixer injection signal frequency. The local oscillator signal dictates what RF channel the receiver will respond to. Depending on the degree of transmitter/receiver channel flexibility required, one or two PLL synthesizers may make up the channel control function. Also, in some design approaches, the data to be transmitted ($T_X$ data) may also be applied to the program input of the PLL that is controlling the transmit channel frequency (dashed connection in Figure 1).

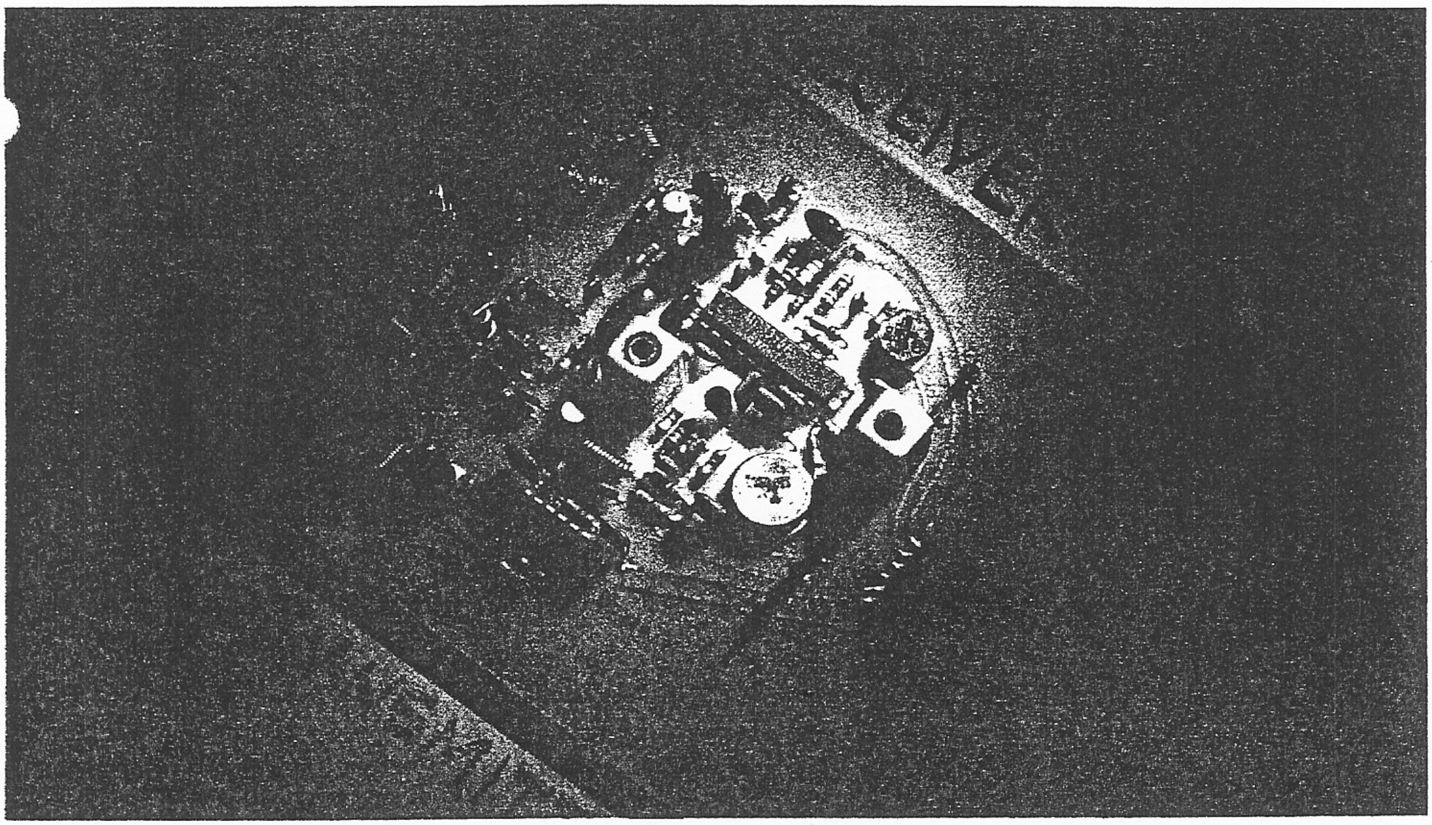
Non frequency agile modems are intended for operation on only one RF channel (or in some instances perhaps two or three channels at the most) and the frequency synthesizer channel control function is not required. Instead, crystal or ceramic resonator controlled oscillators are used to set up the operating channel frequency. A different resonating element/oscillator must be provided if one wishes to cause the modem to operate on another channel. This can be accomplished by physically changing the appropriate circuit elements or by electrically selecting between channel elements that are provided in a multiple fashion within the modem itself. A single channel modem can be produced for less cost than a frequency agile modem but this cost differential diminishes rapidly as the number of operating channels is increased.

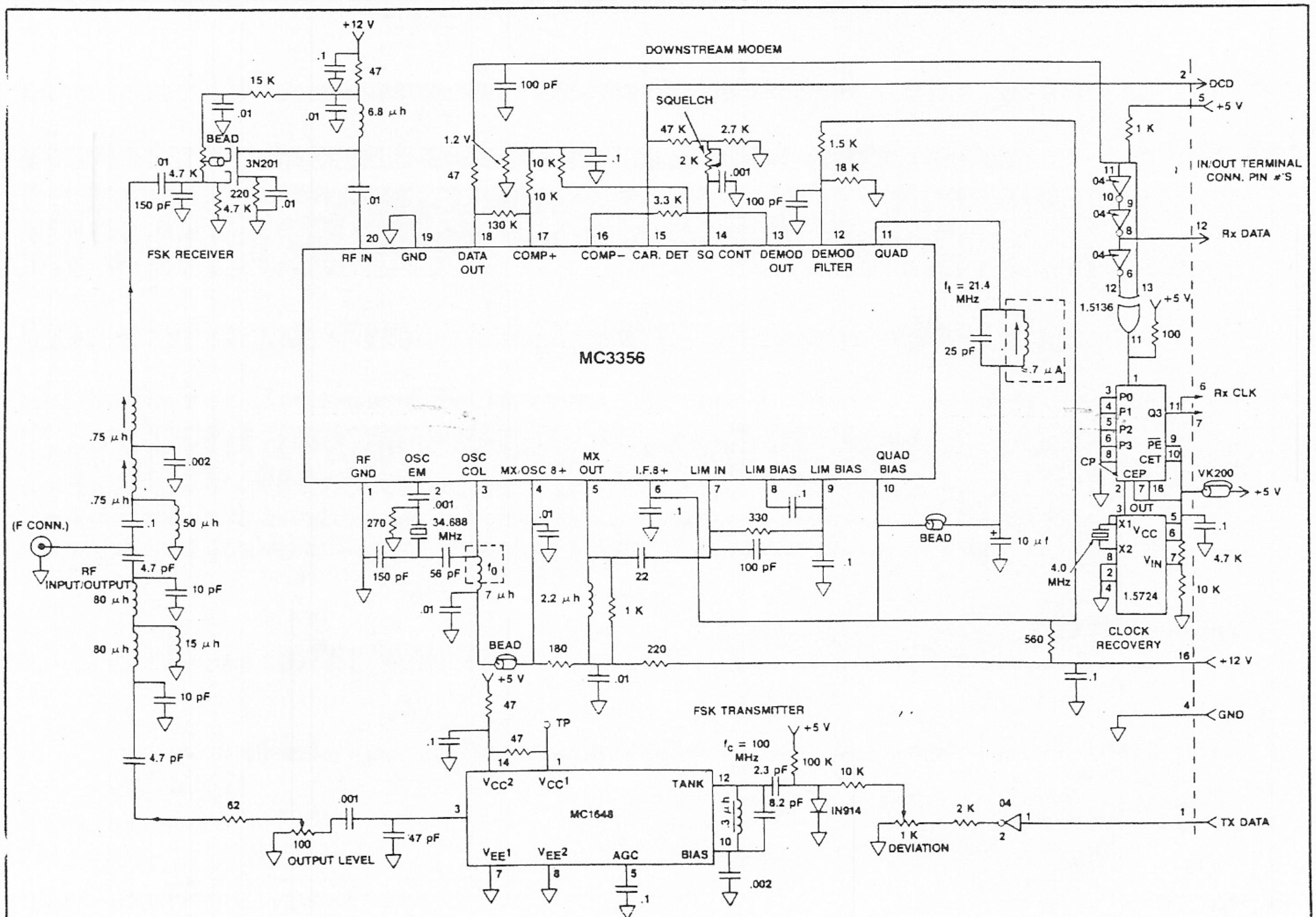
## System and Cost Trade-offs

The most important RF modem characteristics to be considered are:

- Number of channels.
- Maximum data rate.
- Channel frequency values/frequency range.
- Paired or independent transmit/receive channel frequencies.
- Transmit/receive frequency offset value.

All of the above must be traded-off against modem cost and suitability for a particular application.





+12 V
DOWNSTREAM MODEM
SQUELCH
FSK RECEIVER
3N201
BEAD
MC3356
RF IN
GND
DATA OUT
COMP+
COMP−
CAR. DET
SQ CONT
DEMOD OUT
DEMOD FILTER
QUAD
RF GND
OSC EM
OSC COL
MX/OSC 8+
MX OUT
I.F.8+
LIM IN
LIM BIAS
QUAD BIAS
$f_t$ = 21.4 MHz
34.688 MHz
(F CONN.)
RF INPUT/OUTPUT
DCD
IN/OUT TERMINAL CONN. PIN #'S
Rx DATA
Rx CLK
VK200
CLOCK RECOVERY
4.0 MHz
1.5724
1.5136
GND
FSK TRANSMITTER
$f_c$ = 100 MHz
MC1648
TANK
AGC
BIAS
IN914
DEVIATION
OUTPUT LEVEL
TX DATA
TP


FIG 3-2 (B)

The number of channels the modem is capable of being programmed to operate on dictates if a phase-locked-loop (PLL) frequency synthesizer must be incorporated in the design. No synthesizer is needed for single channel operation while greater than three channels will normally require a synthesized approach. Two and three channels units fall into the "gray" area. However, even if not required for channel generation, a PLL may sometimes still be incorporated as the method of generating an FSK modulated carrier for transmission. With the advent of economical LSI PLL ICs and low cost prescaler devices, the use of one or more PLLs does not necessarily mean the modem will be overly expensive.

Although system requirements may dictate a multi-channel modem, cost trade-offs still exsit since the transmitter and receiver can be designed so that channel control is available to each one independently (fully frequency agile) or so that the transmitter and receiver are controlled together with a fixed frequency offset between their respective channels (paired channel operation). For paired channel designs, the choice of transmit/receive offset will impact cost.

The *number* of operating channels alone does not, however, tell the whole story. One "X" channel modem may be significantly more complicated than another "X" channel modem — the actual frequency values involved and also the frequency spread or bandwidth over which the modem must perform can be of equal or greater importance is setting cost. Closely related to these issues is the modem's maximum data rate specification. Higher channel data rates require greater bandwidth per channel and thus a wider total frequency range for a given number of channels. It is worth noting that, for a given total system bandwidth, a small number of high data rate channels will give greater total data output than a large number of lower rate channels. This is because a portion of the system bandwidth must always be devoted to guardbands between adjacent channels. This portion of bandwidth becomes greater, of course, as the number of channels increases. In addition to increased bandwidth requirements per channel, higher data rate signals also tend to be more difficult and expensive to generate and to receive.

The wider bandwidth requirement imposed upon the modem's receiver by higher data rates can affect the choice of frequency for the receiver's IF. Relationships exist between the IF filter's passband and center frequency that must be adhered to. Also, the receiver's IF value and all signal frequencies present at the receiver's input (both desired and undesired) set the location and severity of receiver spurious responses and the

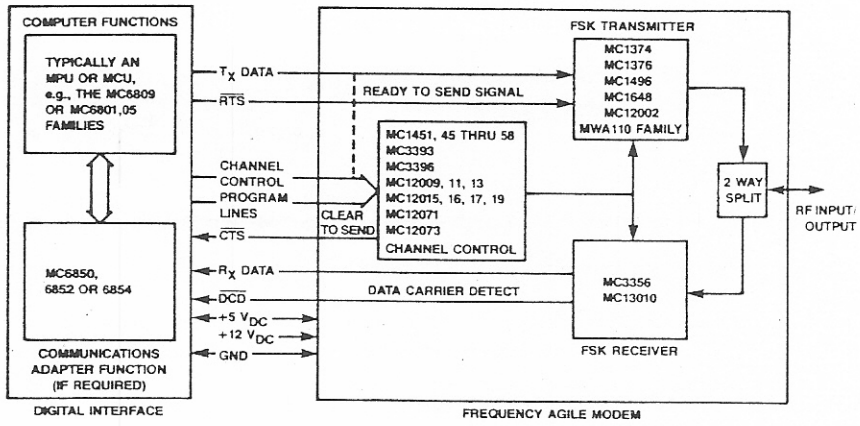



**Figure 1** FREQUENCY AGILE RF MODEM/DIGITAL INTERFACE SYSTEM DIAGRAM ALONG WITH SEVERAL ICS PERTINENT TO IMPLEMENTING THE MAJOR FUNCTIONS

degree of receiver front end filtering that will be necessary for adequate performance.

Although the above trade-offs must be dealt with, the application will usually fix many of the key items such as maximum data rate, channel frequencies, and number of channels. This makes it easier to "zero in" on the remaining considerations.

In general, one may summarize as follows:

- Lowest cost units can support data rates up to approximately 200 Kbits per second. This breakpoint is set by the bandwidth limit if available low cost FM broadcast receiver IF filters.
- For lowest cost, receive channel frequencies should be less than approximately 150 MHz and receiver IF value less than approximately 30 MHz. These breakpoints allow economical data receiver ICs such as MC3356 to be used.
- Modem cost can be expected to rise as the bandwidth over which the modem's RF channels fall increases.
- Other things being equal, a lowest to highest cost progression can be expected for single channel, frequency agile paired channels and fully frequency agile modems, respectively.
- A substantial portion of the increased cost for wider bandwidth and higher frequency can be attributed to the filters and crystals required rather than the semiconductor content.

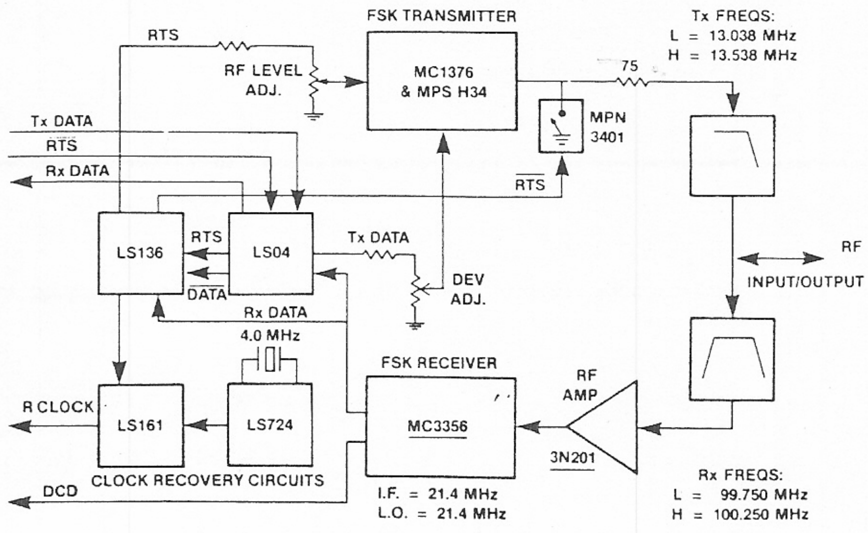



**Figure 2(a)**

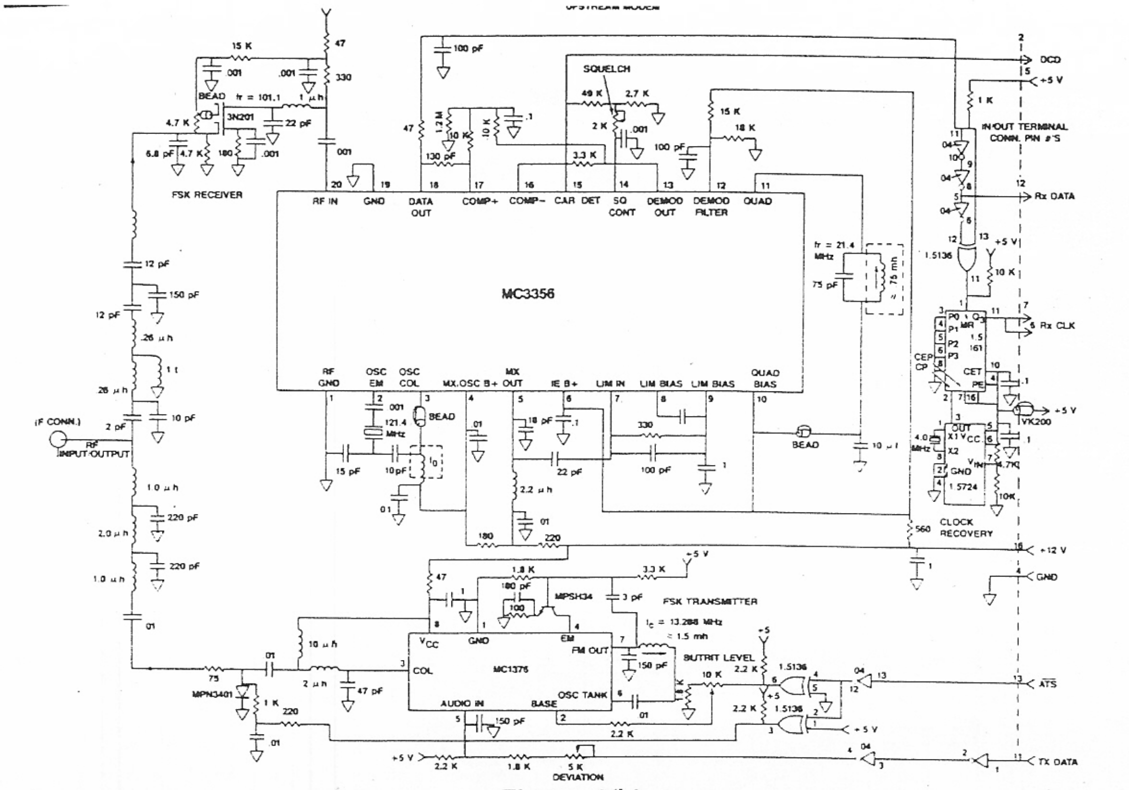
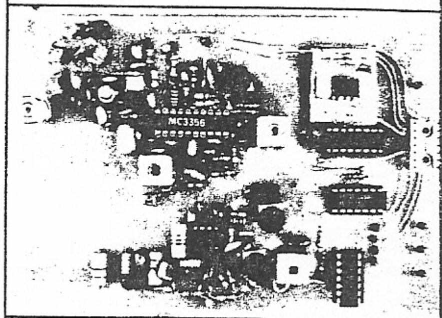



Figure 2(b)



As one would expect, cost of the digital interface functions is also substantially influenced by the data rate ($T_X$ data and $R_X$ data speeds). Other parameters being equal, some of the cost breakpoints for these functions can be estimated to be at about 10 Kbps (low cost MCUs such as the MC6852). Actually, the capability level and therefore cost of the digital interface circuitry is frequently dictated by system needs other than those of the RF modems. It is thus usually best not to include this cost factor as part of the modem's cost when arriving at modem performance/cost trade-offs.

## Modulation Approaches

RF modem designs can employ any one (or variations thereof) of the three modulation methods: Amplitude Modulation (AM), Phase Modulation (PM), and Frequency Modulation (FM).

AM receivers or demodulators are susceptible to errors from impulse noise which is prevalent in digital systems. FM and PM are rather impulse noise immune once the receiver signal is great enough to cause IF limiting to occur. Phase modulation requires a somewhat complex receiver/demodulator to recover the data. Being complex, it is not as cost-effective as a frequency modulated system.

Even though FM may require slightly wider bandwidths than corresponding AM or PM system, it is employed in many applications because it is more effective than AM in combatting noise and interference and more cost-effective than a corresponding PM system.

A simple form of frequency modulation occurs when the modulating signal is a binary serial data stream. The frequency of the carrier is made to shift between two values, one occurring when the data is high and the other when the data is low. Such a binary FM system is referred to as a frequency-shift-keyed (FSK) system.

After considering cost, bandwidth requirements, impulse noise susceptibility, and the availability of proper transmitter and receiver parts, FSK modulation was selected for the RF modem designs described in the following sections.

## FSK Transmitters

Four means of generating RF carrier signals for FSK transmission are:

- L/C Oscillator — The simplest but typically can be used only when a small number of channels are required and when the channel bandwidth allocation is great enough to allow the frequency deviation to be a large percentage of the carrier frequency. This allows for proper data recovery even though the carrier's center frequency is not extremely stable. The single channel modems described in Figures 2 and 3 employ this approach.
- Ceramic Resonator Stabilized Oscillator — Can be used for system requiring more frequency stability than is possible with the L/C oscillator method. A greater limit on the amount of frequency deviation than can be achieved is also imposed. An example of this approach will be presented in Part II.
- Crystal Oscillator Followed by a Digital Counter — The data to be transmitted causes the counter to divide the oscillator's frequency by one of two possible values when the data is a logic "high" and by the other value when the data is a logic "low." The single channel modem in Figure 5 uses this technique and employs a ÷10/÷11 dual-modulus prescaler for the counter function. This approach can provide a very accurate and stable FSK signal. However, it also has its limitations since the data rate, frequency deviation, counter divide values and the oscillator's frequency are all interrelated. This results in both upper *and lower* limits on maximum data rates and transmitter carrier frequencies that can be achieved with practical oscillator values.
- Novel Phase-Locked-Loop (PLL) approach — Provides a way of achieving a high degree of flexibility while still maintaining frequency stability. Both the loop's VCO and progammable counter in the feedback path are modified by the data to be transmitted, This technique allows frequency modulation of the loop VCO with non-symmetrical binary waveforms and is thus capable of processing NRZ data without and baseband encoding. This method will also be explored in Part II.

## Non Frequency Agile Modems

The designation "non frequency agile" .scribes modems that operate on only a single RF channel (or a transmit/receive channel pair). To cause this type of modem to operate on a different RF channel usually requires physically changing certain frequency controlling elements, e.g. the crystal(s). However, it is sometimes economical to consider a "single channel" design for operation on two or poerhaps three channel pairs. This can be accomplished by adding the necessary frequency establishing elements for each channel to the modem and switching them in/out as appropriate by:

- Physically changing the appropriate circuit elements that control frequency.
- Electrically selecting between the frequency establishing circuit elements. This requires that all the appropriate elements be contained within the modem for each operating channel and that a means of selection be provided.

At a minimum, either of the above methods will require changing to one or more new crystals or other resonating elements for each additional channel of ıeration. In the case of switching elec-..onically, switches exhibiting large on/off impedance ratios are required. With either approach, care must be taken during the modem design to use circuit techniques that are sufficiently broadband to allow operation over the intended RF range. This becomes difficult and impractical for wide frequency changes. However, for two or three channels (or transmit/receive channel pairs) that are closely spaced, either of the above approaches should be considered. For a greater number of operating channels or channels that are widely separated in frequency, a frequency synthesizer design approach should be employed.

## Single Channel, 250 Kbps, CATV Modem Pairs

The terms "upstream" and "downstream" are frequently used in relation to CATV networks. They are also applied to modems used in these networks. An "upstream" modem resides at a subscriber's locations and a "downstream" modem is part of the headend equipment. CATV system requirements generally dictate that upstream modems ınsmit on frequencies below 30 MHz and receive on frequencies greater than 54 MHz. A typical receive channel frequency will fall in the vicinity of 100 to 120

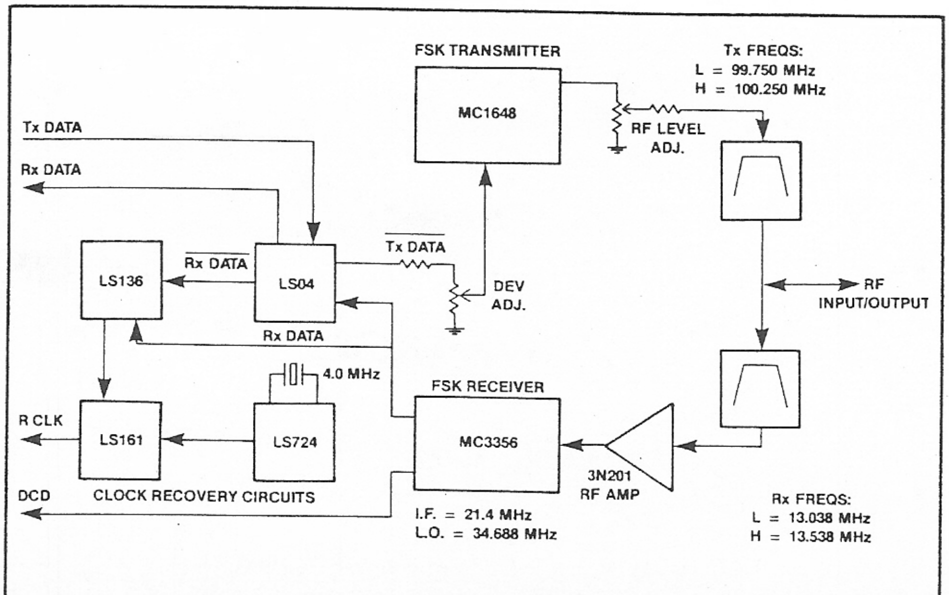



**Figure 3(a) SINGLE CHANNEL, 250 KBPS DOWNSTREAM MODEM BLOCK DIAGRAM**

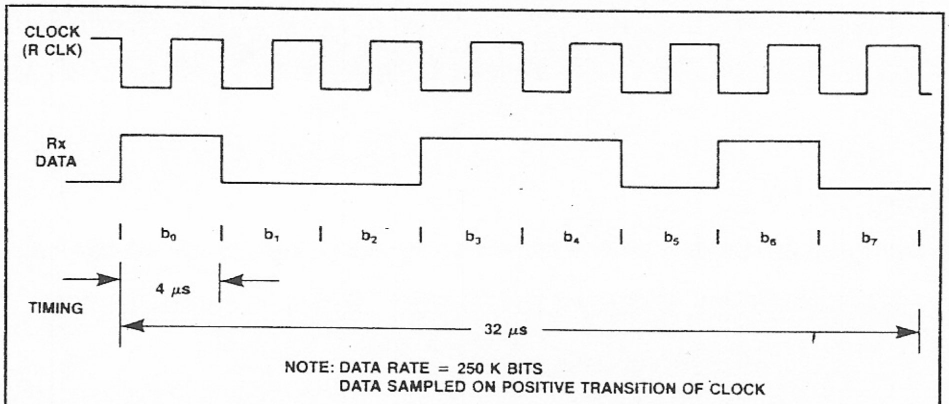



**Figure 4 RECEIVED DATA AND GENERATED CLOCK WAVEFORMS**

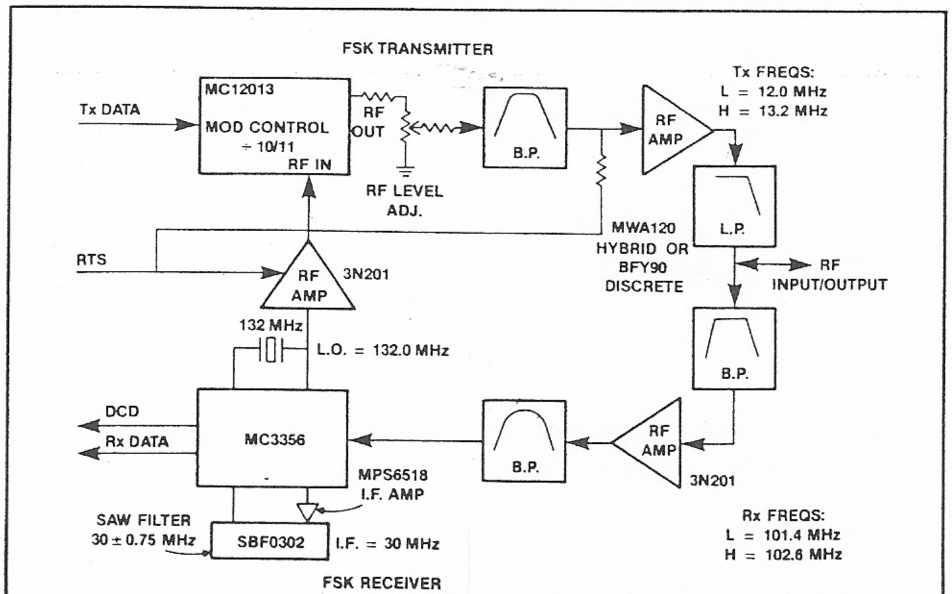



**Figure 5(a) SINGLE CHANNEL, 1.5 MPBS, UPSTREAM MODEM BLOCK DIAGRAM**

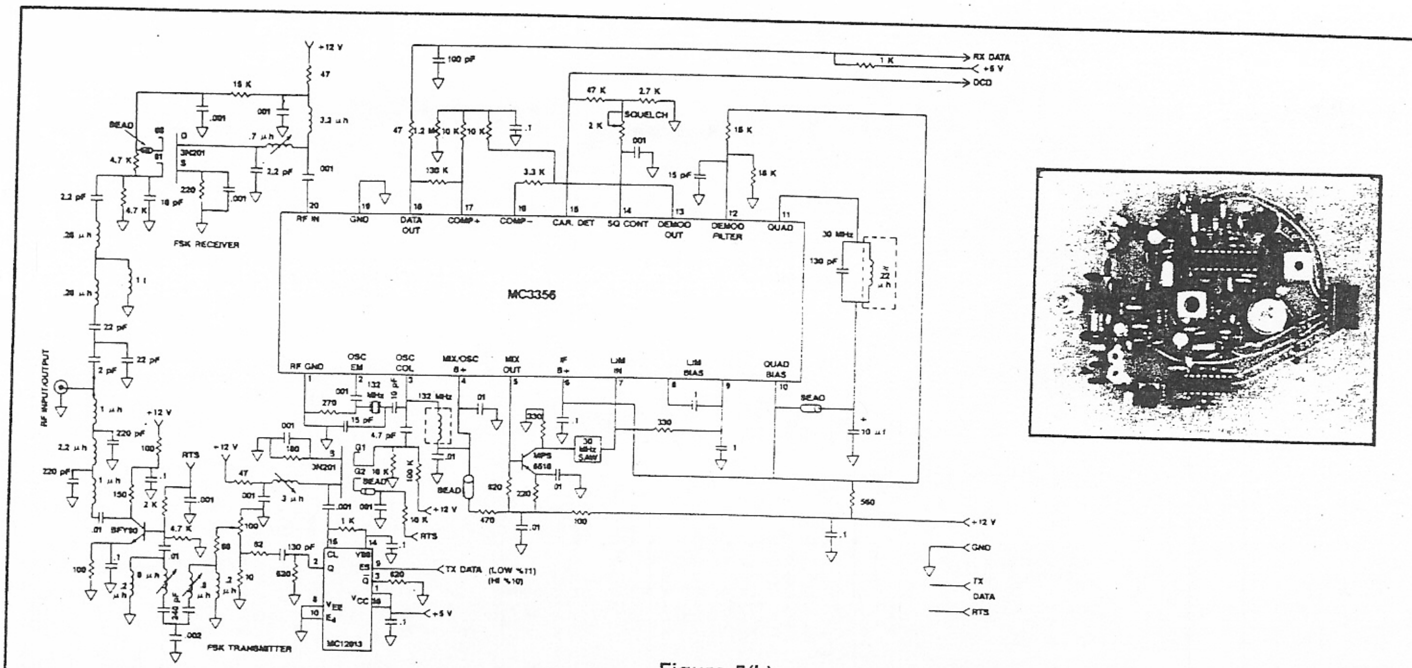



Figure 5(b)

MHz. The downstream modem transmits/receives on the exact opposite frequencies i.e. the receive/transmit frequencies of the upstream modem.

The modem described in Figure 2 can be considered an upstream modem and the design in Figure 3 a downstream modem. Their characteristics are summarized in Table 1. Both modems represent low cost designs capable of transmitting/receiving up to 250 Kbits per second of FSK data. Primarily, each of the modems requires only two ICs — the MC3356 data receiver and either the MC1376 (upstream modem) or the MC1648 (downstream modem) for use as the FSK transmitter. The LS devices indicated are essentially used for recovering a clock from the received data — a feature that can be considered separate from the RF modem itself. The upstream modem is described as having a transmit center frequency of 13.288 MHz and a receive center frequency of 100.000 MHz. The downstream modem operates on just the opposite frequency pair, Both modems employ 21.4 MHz for their receiver IF. Other frequency choices, within limits of the ICs, can also be employed using the same design approach.

Both the upstream and downstream modems employ similar sections using MC3356 with a discrete 3N201 RF front end gain stage tuned to the frequency of interest. The IF filters for the receivers (MC3356 pins 5, 7) are implemented using LC components. One may wish to use ceramic or SAW filters for these functions to improve band shaping and system signal to noise performance. Both receiver local oscillators (MC3356 pins 2, 3) are crystal controlled and require no adjustments. Neither transmitter, however, is crystal controlled. This is only ac-

## IC'S USEFUL IN RF MODEM DESIGN

Receiver

- The MC3356 is a wideband FM receiver designed for use in digital data communications equipment. It includes an oscillator, mixer, limiting IF amplifier, quadrature detector, squelch, and data shaper comparator and is useful for RF inputs to over 150 MHz and IF value to approximately 30 MHz. Its -3 dB limiting sensitivity at 100 MHz is 30 μVrms (20 pin DIP).
- The MC13010 TV parallel sound IF includes a preamplifier, IF amplifier useful to over 80 MHz, quadrature AFT (automatic fine tuning) detector, and AGC outputs. The AFT output can be used to drive external data shaping circuits to provide the modem's received data output. The 13010 can be used when system requirements force the receiver's IF value to exceed the MC3356's capability (18 pin DIP).

**Transmitter**

- The MC1374 RF modulator includes an FM audio modulator, low and high frequency RF oscillators and a dual input RF modulator which can also serve as a doubly balanced mixer. The low frequency oscillator is useful to over 14 MHz and the high frequency oscillator and mixer to over 100 MHz.

In a typical RF modem application, the FM modulator and low frequency oscillator are used to form an FSK signal which is frequency converted in the mixer by adding/subtracting the two oscillator signals. The high frequency oscillator can serve as a VCO with the action of an external varactor diode (14 pin DIP).

- The MC1376 FM modulator includes the FM audio modulator and low frequency oscillator functions of the MC1374 described above (8 pin DIP).
- The MC1496 balanced modulator-demodulator can also serve as a doubly balanced mixer. Useful to over 100 MHz (14 pin DIP, 10 pin metal can).
- The MC1648 voltage controlled oscillator is a low noise design and includes an output buffer. Its frequency is determined by an external tank circuit which includes a varactor diode. The device is useful to over 200 MHz (14 pin DIP).
- The MC12002 double balanced mixer includes an input buffer amplifier and temperature compensated bias regulator. It is useful to over 400 MHz (14 pin DIP).

**Channel Control**

- The MC145145 thru 58 LSI CMOS PLL frequency synthesizer family consists of eight members. Each includes a crystal reference oscillator, reference frequency divider, digital phase detector and at least one programmable counter as well as other functions. Depending on the device, the reference divider is either fully programmable or provides eight preselected values.

All devices are specified for 15 MHz min. over -40°C to +85°C at 5 $V_{DC}$. Higher speeds are possible for higher supply voltages (to 10 volts maximum). Five of the devices are configured to control an external dual modulus prescaler which can extend their programmable counter capabilities to 1 GHz. The other five are intended for use without a prescaler or with a fixed value (single modulus) prescaler.

Three methods of programming are available: Four data bits combined with three address bits; a clocked, serial data stream; or fully parallel (14 or 16 bits). Package sizes range from 16 to 24 pins.

- Single modulus prescalers:

| Device | Divide Values | Typical Max. Freq. (MHz) | Pkg. Pins |
|---|---|---|---|
| MC3396 | 20 | 200 | 8 |
| MC12023 | 64 | 225 | 8 |
| MC12071 | 64, 256 | 300, 950 | 14 |
| MC12073 | 64 | 1100 | 8 |
| MC12074 | 256 | 1100 | 8 |

- Dual modulus prescalers:

| Device | Divide Values | Typical Max. Freq. (MHz) | Pkg. Pins |
|---|---|---|---|
| MC3393 | 15/16 | 140 | 8 |
| MC12009 | 5/6 | 500 | 16 |
| MC12011 | 8/9 | 550 | 16 |
| MC12013 | 10/11 | 600 | 16 |
| MC12015 | 32/33 | 225 | 8 |
| MC12016 | 40/41 | 225 | 8 |
| MC12017 | 64/65 | 225 | 8 |
| MC12018 | 128/129 | 520 | 8 |
| MC12019 | 20/21 | 225 | 8 |
| MC12022 | 128/129 | 1000 | 8 |

**TABLE 1**
**SUMMARY OF CHARACTERISTICS FOR THE RF MODEMS DESCRIBED IN FIGURES 2 AND 3**

| | |
|---|---|
| | **General** |
| Type: | Single channel |
| Maximum Data Rate: | 250 Kbits/second (NRZ. other) |
| Modulation: | FSK |
| Frequency Deviation: | 500 KHz (adjustable) |
| Transmitter RF Output: | 0 to 35 dBmV (adjustable) |
| Input/Output Impedance: | 75 ohms nominal (in band) |
| Clock: | 250 KHz, synchronized on edges of received data. Positive going clock edges give timing for data sampling. |
| Receiver IF: | 21.4 MHz |
| | **Upstream Modem (Figure 2)** |
| **Inputs** | |
| Power: | +5$V_{DC}$ (terminal 5); +12$V_{DC}$ (terminal 16); GND (terminal 4) |
| RTS: | Low enables, high disables transmitter (terminal 13) |
| $T_x$ Data: | Serial data to FSK transmitter (terminal 11) |
| RF Input: | Receiver input (F connector); data high = 100.250 MHz, data low = 99.750 MHz |
| **Outputs** | |
| RF Output: | Transmitter output (F connector); data high = 13.538 MHz, data low = 13.038 MHz |
| DCD: | Data carrier detect — High in the presence of a received carrier (terminal 2) |
| $R_x$ Data: | Received data — Demodulation of received FSK RF input signal (terminal 12) |
| R CLK: | 250 KHz receive clock described above (terminals 6 and 7) |
| | **Downstream Modem (Figure 3)** |
| **Inputs** | |
| Power: | Same as above |
| RTS: | Now used — transmitter always enabled when power is supplied |
| $T_x$ Data: | Same as above |
| RF Input: | Like above except data high = 13.538 MHz, data low = 13.038 MHz |
| **Outputs** | |
| RF Output: | Like above except data high = 100.250 MHz, data low = 99.750 MHz |
| DCD: | Same as above |
| $R_x$ Data: | Same as above |
| R CLK: | Same as above |

**TABLE 2**
**SUMMARY OF CHARACTERISTICS FOR THE RF MODEM DESCRIBED IN FIGURE 5**

| | |
|---|---|
| | **General** |
| Type: | Single channel |
| Maximum Data Rate: | 1.5 Kbits/second (NRZ, other) |
| Modulation: | FSK |
| Frequency Deviation: | 1.2 MHz |
| Transmitter RF Output: | 0 to 35 dBmV (adjustable) |
| Input/Output Impedance: | 75 ohms nominal (in band) |
| | 30.0 MHz center, -3 dB BW = 1.5 MHz — Boith set by SAW filter (Toshiba SBF0302) |
| Receiver Mixer Injection: | High side, 132.0 MHz |
| Crystal: | Overtone, 132.0 MHz |
| Receiver Spurs: | Image = 162 MHz, Half IF = 117 and 147 MHz |
| | **Inputs** |
| Power: | +5$V_{DC}$, +12$V_{DC}$, GND |
| $T_x$ Data: | Serial data to FSK transmitter |
| RTS: | Ready to send signal — High enables, low disables transmitter |
| RF Input: | Input for FSK receiver: data high =102.6 MHz, data low ³ 101.4 MHz |
| | **Outputs** |
| RF Output: | Transmitter output: data high = 13.2 MHz, data low = 12.0 MHz |
| DCD: | Data carrier detect — High in the presence of a received carrier |
| $R_x$ data: | RF input signal |

ceptable when proper shifts in carrier frequency are used in representing the digital data and when adequate system bandwidth and receiver IF bandwidth allowances are made to accommodate the potential frequency inaccuracies. In general, crystal or ceramic resonator controlled transmitter designs should be employed.

The clock circuitry generates a 250 kHz clock from the received data. It is synchronized on transitions of the incoming received data as shown by the waveforms in Figure 4. An appropriate data sample time is established by the clock's positive going edges.

## Single Channel, 1.5 Mbps, Modem

The 1.5 Mbit RF modem illustrated in Figure 5 needs only two ICs and four discrete gain stages. The design receives and transmits on center frequencies of 102 MHz (CATV channel A-3) and 12.6 MHz respectively. Additional performance and operation characteristics are given in Table 2.

Both the modem's receiver and transmitter are crystal controlled by a single oscillator located in the MC3356 data receiver IC. The FSK transmit signal is achieved by dividing this oscillator's frequency by either ten ($T_X$ data line high) or by eleven ($T_X$ data line low). Proper division is accomplished by the MC12013 dual-modulus IC. The same oscillator provides the injection signal for the receiver's mixer which converts the incoming RF to the receiver's IF passband. The mixer and IF functions as well as the limiter, FSK demodulator and data shaping circuits are also contained in the MC3356.

The receiver 30 MHz IF frequency allows the use of a standard SAW filter which has reasonably optimum bandwidth to support a 1.5 Mbit data rate. However, 30 MHz is somewhat higher and the filter insertion loss greater than desired for the MC3356 and therefore additional IF gain is provided external to the IC by the MPS6518 stage (MC3356 pin 5).

The transmitter's RF output amplifier can be implemented using a discrete design as shown in Figure 5b or with a broadband hybrid amplifier gain block such as the MWA120 which is packaged in a three terminal metal can. RF transmission is inhibited by taking the RTS input line low. This renders both the transmitter's output amplifier and 3N201 input buffer amplifier inactive.

Part II to be included in the next issue (Nov/Dec 84) will cover multiple channel (frequency agile) RF modem designs.

### About the Authors

John Hatchett, Member of Technical Staff with Motorola's Semiconductor Products Sector, is responsible for the systems engineering that leads to the definition, development and application of semiconductors in communication and home electronics equipment. A member of the Society of Professional Engineers, Hatchett received his BSEE degree from the University of Illinois and his MSEE from the Illinois Institute of Technology; he has been awarded two patents and has a third patent pending.

William J. Howell was born in Perry County, Indiana on June 27, 1933. He received an AAS Degree in Electrical Engineering Technology from Devry Technical Institute in Chicago in 1960. He worked for RCA in the RF Tuner Group at Indianapolis until 1973. In 1973, Howell joined The Motorola Semiconductor Group as an RF Application Engineer, where he is presently employed as a Sr. Staff Engineer in System Engineering Strategic Marketing. Howell has been awarded one patent and has two patents pending.