how it works

DESPITE CLAIMS THAT CLAUDE SHANNON PROVED IT IMPOSSIBLE HALF A CENTURY AGO, VMSK/2 WORKS AND *DOESN'T* VIOLATE INFORMATION THEORY, SAY PROPONENTS. WHEN PROPERLY IMPLEMENTED AND USED UNDER THE RIGHT CONDITIONS, THE DIGITAL MODULATION SCHEME REPORTEDLY DELIVERS 90 BPS/HZ—OVER THE AIR.

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VMSK/2: high bps, low BW, (allegedly) no snake oil

By Dan Strassberg, Senior Technical Editor

THAT 56-KBPS MODEM IN YOUR PC (well, it *would* be a 56-kbps modem were it not for restrictions on crosstalk among wire pairs in telephone cables) can theoretically deliver almost 19 bps/Hz (bits per second per hertz of phone-line bandwidth). Nearly four years ago, when these modems first appeared, their ability to push data so rapidly through a telephone line's 3-kHz bandwidth left consumers awe-struck. You might think that wireless communication, with its plethora of interfering sources and signal impairments, wouldn't permit bandwidth efficiencies close to those of the fastest modems.

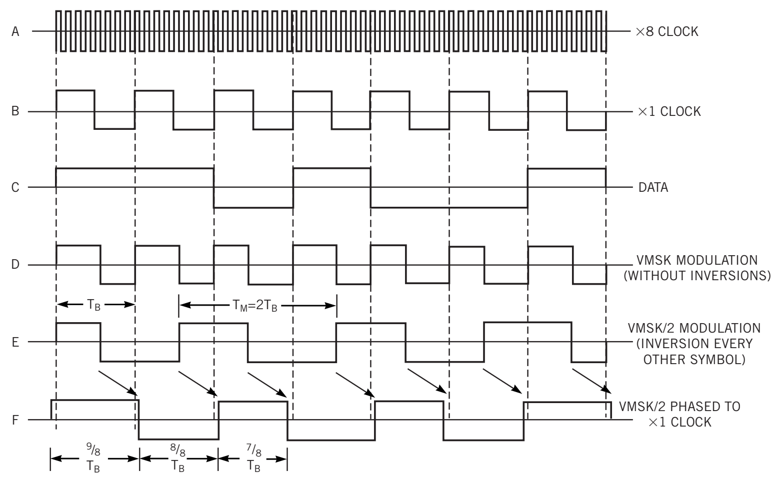

Figure 1

To generate VMSK/2 coding, you first generate a duty-cycle-modulated signal (D) that begins each period in the high state. The portion of the time the signal spends in that state is determined by the data (1 or 0) and is either slightly greater than or slightly less than 50%. You then invert the signal in all of the even-numbered intervals (E). Finally, you delay the signal (F) so that its edges either slightly precede or slightly follow the edges of the times-one clock (B). In this example, signal D has a duty cycle of either $^5/_8$ or $^3/_8$ of the times-one clock period, T_B. Signals E and F thus spend $(n+x)T_B$ in the high or low state (where n is any integer ≥ 0 and $x = {}^7/_8, {}^8/_8$, or $^9/_8$).

Now, however, a modulation technique called VMSK/2, which encounters filtering problems at baseband and thus initially targeted wireless applications, promises bandwidth efficiencies as great as 90 bps/Hz. This efficiency is almost five times that of a 56-kbps modem. The technique's proponents are now also promoting wire-line applications, inserting a carrier at the receiving end of the line to circumvent the filtering problems that are inherent at baseband. VMSK/2 (one-half very minimum phase-shift keying, also called AAPSK, or alternate-aperture phase-shift keying) and its progenitor, VMSK, are forms of single-sideband, suppressed-carrier, biphase modulation.

An example drawn from radio broadcasting provides additional perspective on VMSK/2. Suppose that DAB (digital-audio broadcasting) used VMSK/2, and suppose that DAB stations on what is currently called the FM band transmitted digital audio as 128-kbps MP-3 stereo streams. One stream would occupy 128 kbps/(90 bps/Hz)≃1.42 kHz. In North America, FM channels are nominally 200-kHz wide (though most energy is confined to the center 150 kHz). In theory, then, the numbers suggest that if DAB used VMSK/2, an FM station could simultaneously transmit more than 100 CD-quality 128-kbps MP-3 stereo streams. (Many audio purists insist that 128-kbps MP-3 doesn't come close to CD quality, but millions of users don't seem to notice.) Even a 10-kHz-wide channel, such as those of the Western Hemisphere's AM band (also known as the medium-wave, or MW, band), could transmit seven MP-3 streams.

More aggressive data compression could further reduce the bandwidth requirements. For example, at 96 kbps, Real Networks' (www.real.com) G-2 software codec transmits a stereo signal that many people find indistinguishable from MP-3. With the G-2 codec and a bandwidth efficiency of 90 bps/Hz, a 10-kHz channel could transmit 10 high-quality stereo streams. Note that the choice of codec is more-or-less independent of the modulation technique.

Bandwidth efficiency is a convenient, albeit simplistic and sometimes inaccurate means of quantifying a modulation system's use of bandwidth. For example, because it does not take into account the spectrum shape, the bits-per-second-per-hertz figure can incorrectly predict the minimum feasible channel-to-channel spacing. The VMSK/2 channel spacings mentioned in the preceding paragraphs may be optimistic, but the point of the discussion is not: VMSK/2, say its proponents, makes more efficient use of bandwidth than any other digital-modulation technique.

WIRELESS IS KING—WELL, MAYBE

VMSK/2 advocates use this dramatic example to make their point: The US AMPS (Advanced Mobile Phone System) cellular-telephone standard allocates a bandwidth of 30 kHz to a channel. Although designed for voice, the channel can transmit digital data at 48.6 kbps (although the most common data rate is 14.4 kbps). Using VMSK/2, the channel can transmit 1.544 Mbps, a more than 30- to 100-times improvement that provides data rates approaching those of cable modems. Although VMSK/2's bandwidth efficiency in this example is "only" 50 bps/Hz, the result suggests that wireless technology might prove more practical than either phone lines or cable for providing high-speed Internet access to homes. Now, however, that picture appears to be changing. VMSK/2 advocates are experimenting with wire-line applications and are claiming much greater bandwidth efficiency and hence much greater range than that of DSL (digital-subscriber-line) technology. DSL's range—approximately three miles of wire between the central office and the subscriber—is a true Achilles' heel of DSL technology.

VMSK/2's robustness is a different issue. The scheme's advocates point out that its narrow bandwidth requirements produce high noise immunity and enable VMSK/2 to deliver low BERs (bit-error rates) at much lower transmitter powers than those used with more familiar types of modulation. To be practical for over-the-air use, however, a digital-modulation approach must not only offer good noise immunity, it must also deliver low errors in the presence of such impairments as multipath fading and frequency-dependent phase shift. The literature is largely silent on how these impairments affect VMSK/2 signals, although, as this article went to press, the proponents were completing what they termed highly successful tests at a major cellular-service provider's testing facility. This work purportedly demonstrated significantly greater immunity to impairments than that of competitive modulation techniques.

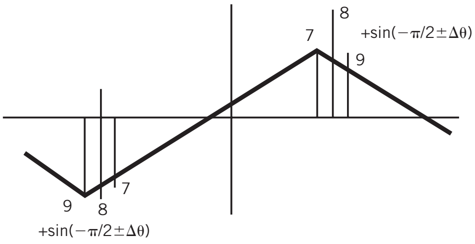

Figure 2 Signal detection (demodulation) involves sensing the points at which the phase of the RF carrier jumps from advanced to retarded or retarded to advanced (with respect to the phase of an unmodulated carrier). The decoder can then generate a triangular wave such as this one. (The time intervals labeled 7, 8, and 9 refer to the conditions of Figure 1.)

Multipath is a significant problem in VHF (very high-frequency) and higher frequency bands. The 88-to-108-MHz FM band occupies a portion of the 30-to-300-MHz VHF spectrum. Frequency-dependent phase shift is a problem in MW bands, such as the current AM band—particularly with skywave reception from distant stations or in the radiation nulls of highly directional stations. Although mathematical analysis, simulation, and laboratory tests provide some insight into a modulation scheme's robustness, the ultimate tests involve field trials under a variety of real-world conditions. Whereas robustness can't ensure a modulation approach's success, inadequate robustness almost certainly kills the system's prospects.

For broadcast applications, another important consideration is VMSK/2's degree of compatibility with the analog modulation currently used in AM and FM radio. Unlike the signals proposed for IBOC (in-band, on-channel) DAB, VMSK/2 signals cannot normally be transmitted simultaneously with analog-broadcast signals on the same channel from the same transmitter. Still, VMSK/2 proponents assert that FM stations can apply VMSK/2 signals to their subcarriers without interfering with the main-channel signal. FM stations use these subcarriers for a variety of purposes, such as transmitting background music to paid subscribers. Leasing the subcarriers is an important source of revenue for many FM stations. The more information the subcarriers can convey, the greater their economic value. The subcarriers are frequency modulated at supersonic frequencies onto the FM station's main carrier. Currently, program material is amplitude modulated onto the subcarriers using full-carrier double-sideband modulation, of the type used in AM radio. The information bandwidth on each subcarrier is limited to approximately 10 kHz. With VMSK/2, each subcarrier can transmit 2.044 Mbps—enough to convey 16 CD-quality MP-3 stereo streams.

ONE BIT PER SYMBOL

So, how does VMSK/2 pack so much information into so little bandwidth? Surprisingly, the technique is a variation on BPSK (bipolar phase-shift keying) and uses a 1-bit-per-symbol format. Most people associate high bandwidth efficiency with low symbol rates and multiple bits per symbol, often implemented through the use of subcarriers. However, despite its use of these techniques and its reputation for high bandwidth efficiency, the very popular QAM (quadrature amplitude modulation), transmits many fewer bits per second per hertz than does VMSK/2.

At a given data rate, QAM generally requires higher transmitted power to achieve the same BER as VMSK/2. The ratio of the required powers depends on the QAM format's number of bits per symbol. If you hold the data rate and transmitted power constant, increasing the number of bits per symbol decreases the required symbol rate but, in general, increases the BER. To reduce the BER while holding the data rate and bits per symbol constant, you must either increase the transmitted power or use more sophisticated error correction. However, because better error correction uses more bits, you need a somewhat higher raw data rate to achieve equal throughput. This argument applies to bit errors that you can trace to noise. If the source of the errors is ISI (intersymbol interference), such as that which results from multipath fading, the argument does not apply. When ISI is the culprit, increasing the number of bits per symbol and reducing the symbol rate may improve (decrease) the BER at a constant transmitted power.

You can think of VMSK/2 as a form of duty-cycle modulation (**Figure 1**). Think of a "square" wave whose total period does not vary but which, depending on whether a given bit interval contains a 1 or a 0, spends slightly more or slightly less than half the period in the high state. The waveform, of course, spends the rest of the period in the low state. The preceding two sentences actually describe VMSK, the precursor of VMSK/2. VMSK/2 inverts the square wave in every second clock period, thereby reducing the repetition rate of the not-quite-square wave by half. Suppose that in Period 1—and in all odd-numbered periods—the signal starts in the high state and, near the middle of the period, transitions to the low state. Then, in Period 2—and in all even-numbered periods—the signal starts in the low state and, near the middle of the period, transitions back to the high state.

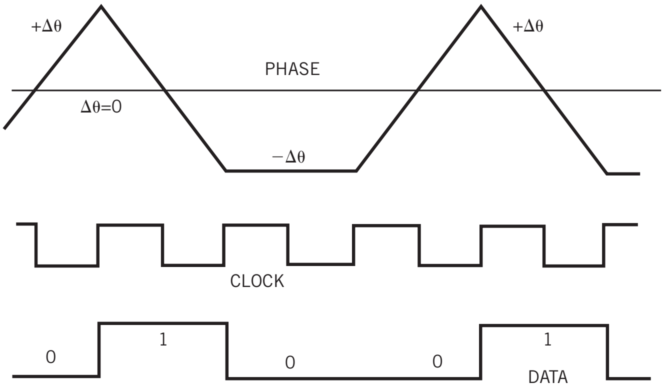

Figure 3 By sampling at the peaks, you can convert directly into ones and zeros the output of an exclusive-OR phase detector whose reference and signal inputs are in quadrature. The sampler's output is ±Δθ, which is the phase change that corresponds to a shift in edge position of $\omega_M T_B/8$, where ω_M is the modulation rate and T_B is the times-one clock period. (See figures 1 and 2.)

In VMSK, you can recover the clock signal—a "perfect" square wave—from the modulated signal by phase locking the clock-recovery circuit to the modulated waveform's low-to-high-state transitions. In VMSK/2, it is somewhat more difficult to derive a square-wave clock at the data rate (that is, at twice the VMSK/2 signal's repetition rate). One way is to pass the duty-cycle-modulated signal first through a bandpass filter that is sharply tuned to the VMSK/2-signal rate, then through a frequency doubler, and finally through an edge detector.

ON TO RF

So far, the discussion has focused on baseband signals. The method by which the baseband signals modulate an RF carrier is equally important to achieving high bandwidth efficiency. In either VMSK or VMSK/2, when the square wave is in the high state, the modulator slightly advances the carrier's phase with respect to the nominal (unmodulated) value. That is, if the unmodulated carrier's zero crossing coincides with the square wave's low-to-high state transition, the carrier is already a few degrees into a half cycle at the beginning of the high-state interval. When the square wave is in the low state, the modulator retards the carrier's phase from the unmodulated value by an equal amount. That is, if the unmodulated carrier's zero crossing coincides with the square wave's high-to-low state transition, the carrier is approaching the end of a half cycle at the beginning of the low-state interval.

There is yet another wrinkle in VMSK/2's bandwidth frugality. The modulated RF signal is filtered to remove one sideband and the carrier, thereby producing a single-sideband, suppressed-carrier signal. Filtering is necessary for another reason too. The unfiltered spectrum also contains wideband noise or "grass." This noise is well below the spectral peak, however. Just how far below depends on the details of the modulator. Values in the vicinity of 35 dB are typical. To comply with FCC (Federal Communications Commission) regulations, the transmitter must limit the noise bandwidth. Doing so affects neither the integrity of the data nor the rate at which it can be transmitted.

You might think that, because the carrier frequency does not change, the transmitted signal's spectrum consists of a single spike. That is, you might theorize that the modulated carrier contains no sidebands. Still, because of the single-sideband filtering, the spectral peak *must* be slightly displaced in frequency from the original carrier frequency. However, you know that a single-frequency signal without sidebands cannot convey information.

The carrier's alternately advanced and retarded phase is, of course, what conveys the information. Sidebands exist, but a spectrum analyzer doesn't display them. When the modulated carrier's phase deviation is less than approximately ±0.2 rads with respect to the unmodulated carrier, the spectrum analyzer cannot resolve the sidebands. More common forms of biphase modulation, such as BPSK, do produce sidebands that you can observe on a spectrum analyzer. BPSK's phase changes are considerably larger than those in VMSK and VMSK/2, however. Depending on whether it is transmitting a 1 or a 0, BPSK reverses or does not reverse the carrier's phase (retards the phase by 180° or does not retard it). If you examine a VMSK/2 RF waveform in the time domain (at least, if you examine it before the final filter), you may see discontinuities at the phase transitions. What you see at any transition depends on where in the carrier cycle the transition occurs. A phase transition always produces a discontinuity in the RF waveform's slope (first derivative), however.

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DEMODULATION

The developers of VMSK/2 have devised several methods of recovering (demodulating) the encoded data from the RF carrier. Although a thorough treatment of VMSK/2 demodulation is beyond the scope of this article, the most easily understood technique involves the use of a phase detector locked to the points in the modulated signal at which advanced phase begins (**Figures 2** and **3**). The detector uses a clock in phase with the original times-one clock (at twice the VMSK/2 square-wave rate) and recovers a signal at the times-one rate (**Figure 4**). The fraction of each cycle that this signal spends in the high state contains the data. Three possible values exist. The longest represents a change of 0 to 1 (compared with the previous cycle). The shortest represents a change from 1 to 0. The intermediate value indicates no change. That is, if the previous cycle contained a 1, then so does the current cycle; if the previous cycle contained a 0, so does the current cycle. This signal appears to contain information that you could use for error-detection (although error-correction would require additional information). If the previous period's data was a 0 and this period's data represents a change from 1 to 0, the data in at least one of the two periods must be incorrect.

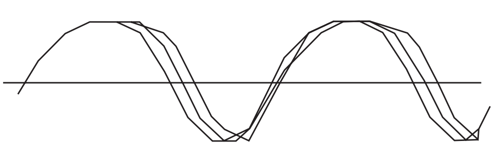

Figure 4

If the demodulator's reference signal is in phase with the times-one clock, the demodulator output resembles a distorted sine wave in which the positive "half-cycle" duration assumes one of three values. The shortest duration represents a change from 1 (in the previous clock period) to 0 (in the current period). The longest duration represents a change from 0 to 1. The intermediate value indicates that the data in the current clock period has not changed from that in the previous period.

There is a great deal more to the subject of VMSK/2 demodulation. The signal processing requires some highly unusual filters that have extremely narrow passbands. The developers call these non-Nyquist filters. Although bandpass realizations of these filters are possible, baseband realizations are not. This characteristic necessitates reinsertion of the carrier frequency in wire-line VMSK/2 receivers. Alphacom Communications (www.networkalpha.com, www.vmskglobal.com, www.vmsknetwork.com) holds patent rights to the non-Nyquist filters and other aspects of VMSK and VMSK/2 technology. The company secured these rights when it acquired Edison, NJ-based Pegasus Data Systems—now known as Alphacom's Pegasus Laboratories Division (1-732-356-9200).□

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