Making a data terminal out of the Touch-Tone telephone

A two-chip dual-tone multiple-frequency receiver plus some other logic can turn the phone into a low-cost remote controller or data-entry system

by Robert A. Broomfield, Thomas Foxall, and Patrick Beirne, *Mitel Semiconductor Inc., Kanata, Ottawa*

□ Touch-Tone keypads, by now an international standard for entry into the worldwide telephone network, also make data communications possible wherever there is a telephone. Essential to this use is the dual-tone multiple-frequency receiver, which processes the two discrete frequencies generated whenever one of the keypad's push buttons is pressed.

Although one- and several-chip approaches to a DTMF receiver already exist, a two-chip version is now being introduced for the first time. Aided by a few external components, this Mitel design—separate filter and decoder chips designated the MT8865 and MT8860, respectively—affords an optimum tradeoff between cost-effectiveness and flexibility.

Like the other chips, the MT8865/8860 offers both the classic telephone functions and many important new ones. It can be used to construct a single-ended or differential DTMF receiver, update older rotary-dial phones by means of tone-to-pulse conversion, and create a call restrictor in an individual telephone or a private branch exchange. But more significantly, it will in the future also serve in many remote control and remote data-entry systems. Examples are the remote control of test, measurement, and industrial equipment and eventually, in the office or home of the future, the remote control of home appliances, alarm systems, and unattended message recorders.

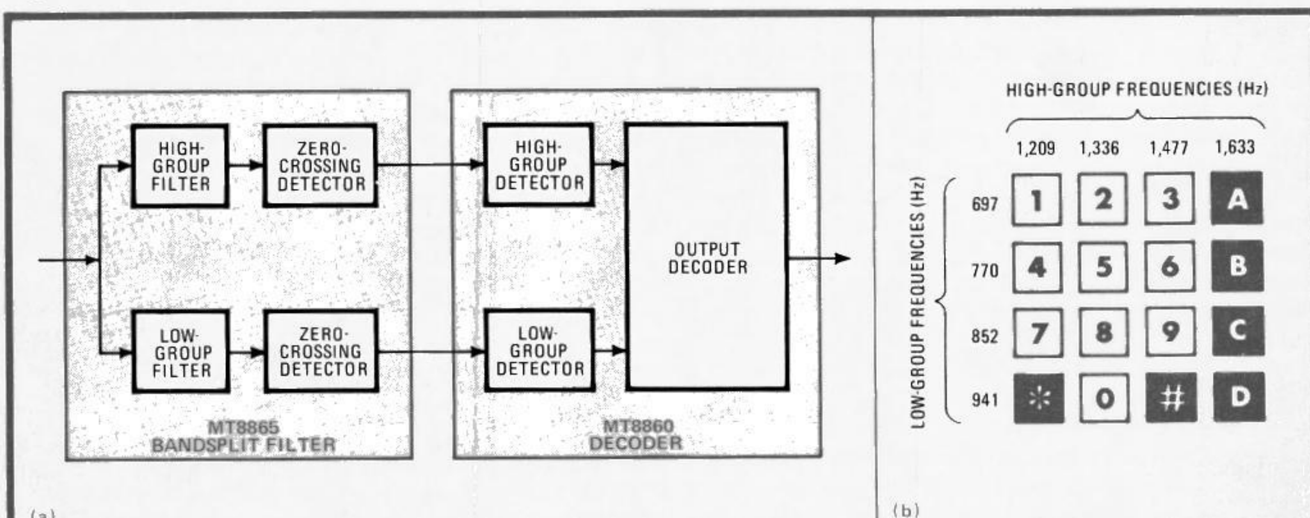
Today DTMF receivers have only a small share of this market. But their potential in the data-communications area is limited only by a designer's imagination.

A proper combination

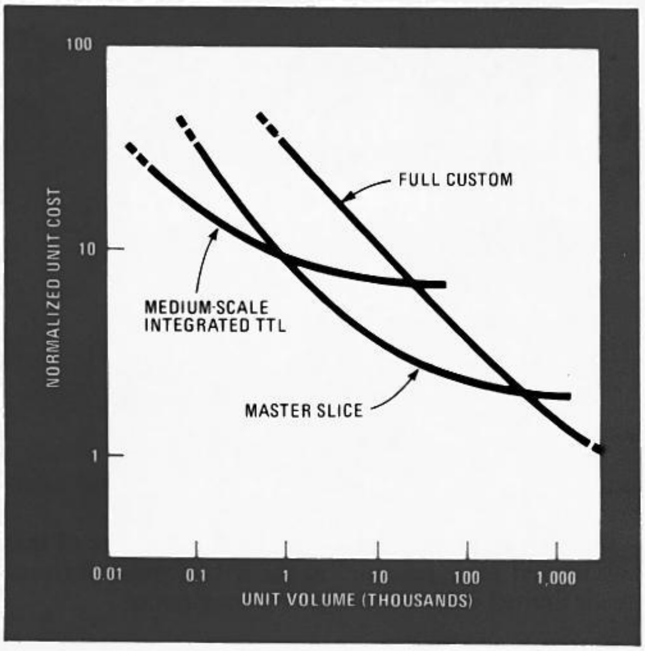
The MT8865 DTMF analog bandsplit filter consists of two bandpass filters plus zero-crossing detectors for the front-end functions of bandsplitting, dial-tone rejection, and limiting. The MT8860 DTMF digital decoder detects and decodes the tones (Fig. 1a). External components tailor the chips for different applications.

A DTMF signal received by the MT8865 is the conventional combination of two tones from the eight frequencies the keypad can generate (Fig. 1b). If there were no additional restrictions, this scheme would allow 28 different tone combinations. But DTMF signaling rules split the tones into two groups of four and restrict the combinations to one tone from each group, limiting the number of possible combinations to 16.

Since it is known that one frequency component lies in the low group of 691 to 941 hertz and the other in the high group of 1,209 to 1,633 Hz, the original tones can be extracted by two fixed bandpass filters, each designed



1. Pick a pair. The Mitel MT8865/8860 dual-tone multiple-frequency receiver chip set (a) decodes the symbols transmitted by a standard three- or four-by-four keypad. The inhibit pin on the 8860 decoder disables detection of the tone pairs generated by the shaded keys (b).



2. Crossovers. For volumes below about 1,000 units, discrete TTL is probably the best approach. For intermediate volumes, the master slice offers the lowest unit cost. At the highest volumes, fully custom chips dominate. The ultimate choice depends upon the application.

definition phase to the working prototypes stage, software debugging and system integration problems can push even a simple microprocessor development cycle out to several months.

Selecting a master slice

Before deciding on a particular master slice, a designer should study a logic diagram and product definition. The required density can be estimated from the logic diagram and the product definition will indicate the performance required. These density and performance criteria, in conjunction with the I/O pin count, will help determine the optimum master-slice technology.

Each technology has its strong and weak points, as outlined back in Table 1. C-MOS technology is the clear leader at present. It can provide packing densities of up to 2,000 gates, 30-MHz toggle rates, and inherent low power consumption. The fan-out of IMI's C-MOS is, however, limited to a few LS TTL loads.

Faster gate arrays are possible with TTL, especially when output drive is an important consideration. However, the speed is attained at the expense of power consumption, which can approach eight times that of C-MOS and more. The power dissipation of TTL tends to limit densities to around 1,200 gates.

Pros and cons

I^2L consumes more power than C-MOS, but less than TTL. Its output drive is attractive, but it is slower than either silicon-gate C-MOS or TTL. It does have some advantages in applications that require both linear and digital circuitry on the same chip. New I^2L products with higher densities are scheduled for introduction soon.

N-channel MOS has potentially the highest density, but this fact has not yet been exploited for commercial master slices. Its output drive and power dissipation are both moderate, but its tolerance of supply-voltage variations is not nearly as great as C-MOS's.

To benefit most from the technology selected, the layout of the master slice must be efficient. Many factors may influence overall efficiency, including transistors per cell, cell area, cell contact access, cell performance, wiring channels between cells, accessability and availability of underpasses, I/O buffers and pads, power busing, internal buffers, and CAD-adaptable grids. A master slice designed for general-purpose logic functions is a complex optimization of these and other issues.

In some cases, the tradeoff is clear; for example, more wiring channels ease interconnection but decrease the chip's transistor density. An increase in the number of I/O pads increases the die size for a given array, but many applications need an abundance of interface pins. One of IBM's master-slice circuits used in its 4300 computer, for example, has 132 I/O pads for a 704-gate array. The use of standard packages may sometimes also limit the number of available pins.

From logic to master slice

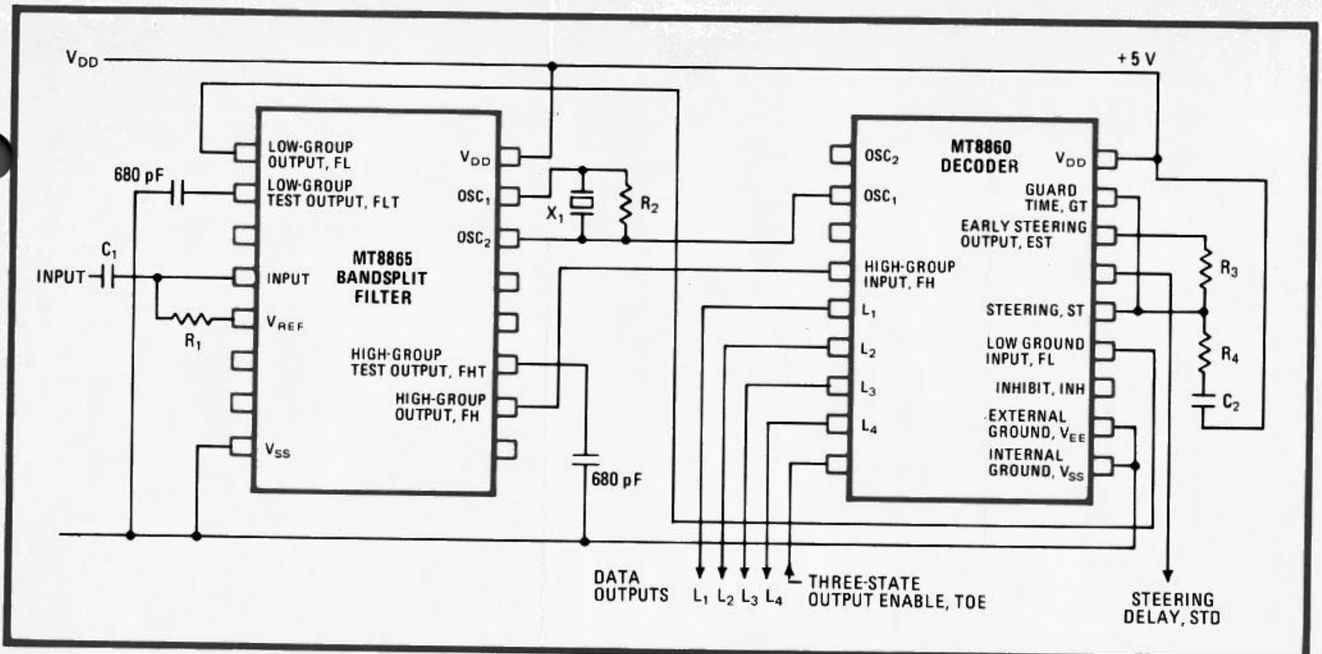
Once a suitable base master slice is selected, the design of the final layer of metal interconnection is undertaken, usually by the supplier. Admittedly, because of each master slice's unique design rules, the final metal patterning process may seem like a black art. Fortunately, CAD systems can now off-load much of this work.

With a CAD system, the digital master-slice design process becomes much more efficient. The interconnection of commonly used functions—such as many types of flip-flops, various gates and gate combinations, counters, and decoders—are stored in a function library. Proceeding on a schematic, the designer calls up logic functions on a cathode-ray-tube terminal. Each function initially appears as a shaded block that is used to further generate an overall placement plan at a magnification of around 20 to 50 times. Interconnection algorithms help the designer with both placement and with the routing of wires between blocks.

Using rules that force wiring into preassigned channels removes a lot of the drudgery of checking. Much of the manual wiring, final design details, and layout checks are performed on the screen at a magnification of 1,000 times or more, with each transistor, wiring path, and contact visible. The CRT screen becomes a movable window through which any portion of the chip can be viewed at any desired resolution. A hard-copy plot may also be generated to show the whole chip or any section.

Finally, a detailed check is made against the input logic diagram. Once the design is complete and correct, the CAD system produces a pattern-generator tape, which produces the final photomasks.

A CAD system can reduce development time for a master-slice design in several ways. For instance, each logic function need not be redesigned every time it is used as each has already been confirmed, checked, and characterized. Also, manual pattern generation—using Mylar tape, for instance—is unnecessary, so a 200-gate master-slice circuit that once took a week or more to complete can now be made in a few hours with CAD. □



2. Single-ended. A basic DTMF receiver may be set up so that both chips are controlled by one 5-volt supply and one external crystal. The minimum component circuit is suitable for application to single-ended devices and requires few external components.

to pass one range only. The two outputs obtained are relatively pure tones, separately limited to produce digital signals or square waves having the same frequencies as the originating tones. Digital counting algorithms are employed to determine the frequency of the received tones accurately. Each group is checked individually for the presence of a DTMF frequency, and when both groups detect a valid tone for a minimum time duration, the circuit decodes the digit that was transmitted.

This detection method is possible only because of the restricted signaling format employed. DTMF receivers that must detect any two out of a number of possible tones are more complicated since they cannot use a simple bandsplit filter to separate the incoming tones.

Inside the filter

The bandsplit filter chip consists of bandpass filters, which split the incoming signals into their component frequencies, and comparator circuitry, to square up the resulting waveforms. It employs switched-capacitor circuit techniques implemented in Mitel's ISO^2-CMOS (double-polysilicon oxide-isolated complementary-MOS) technology. A high-speed, dense, C-MOS process with a linear circuit capability, it is ideal for mixed analog and digital circuits like this filter.

The filter's electrical specifications are more than adequate for the DTMF job. The bandpass ripple is less than 0.75 decibel and intergroup rejection is better than 37 dB. As a bonus, both filters have a notch at 440 Hz to aid in dial-tone rejection. The gain of the filters in the passbands is unity, and comparator levels have been set to ensure 30 dB of dynamic range.

Both the high-group filters and the low-group filters are sixth-order switched-capacitor designs, whose accuracy is a function only of the capacitance ratios and the system clock frequency. Since both of these parameters are well controlled, the filters can be realized very accurately without the need to resort to trimming.

Each sixth-order bandpass filter has three biquad sections. A leapfrog design minimizes filter sensitivity to switched-capacitor sampling-coefficient errors. On the final filter output, this sampling is done at 127.8 kilohertz—a rate that is compatible with the 64-kHz input sampling rate of the digital decoder.

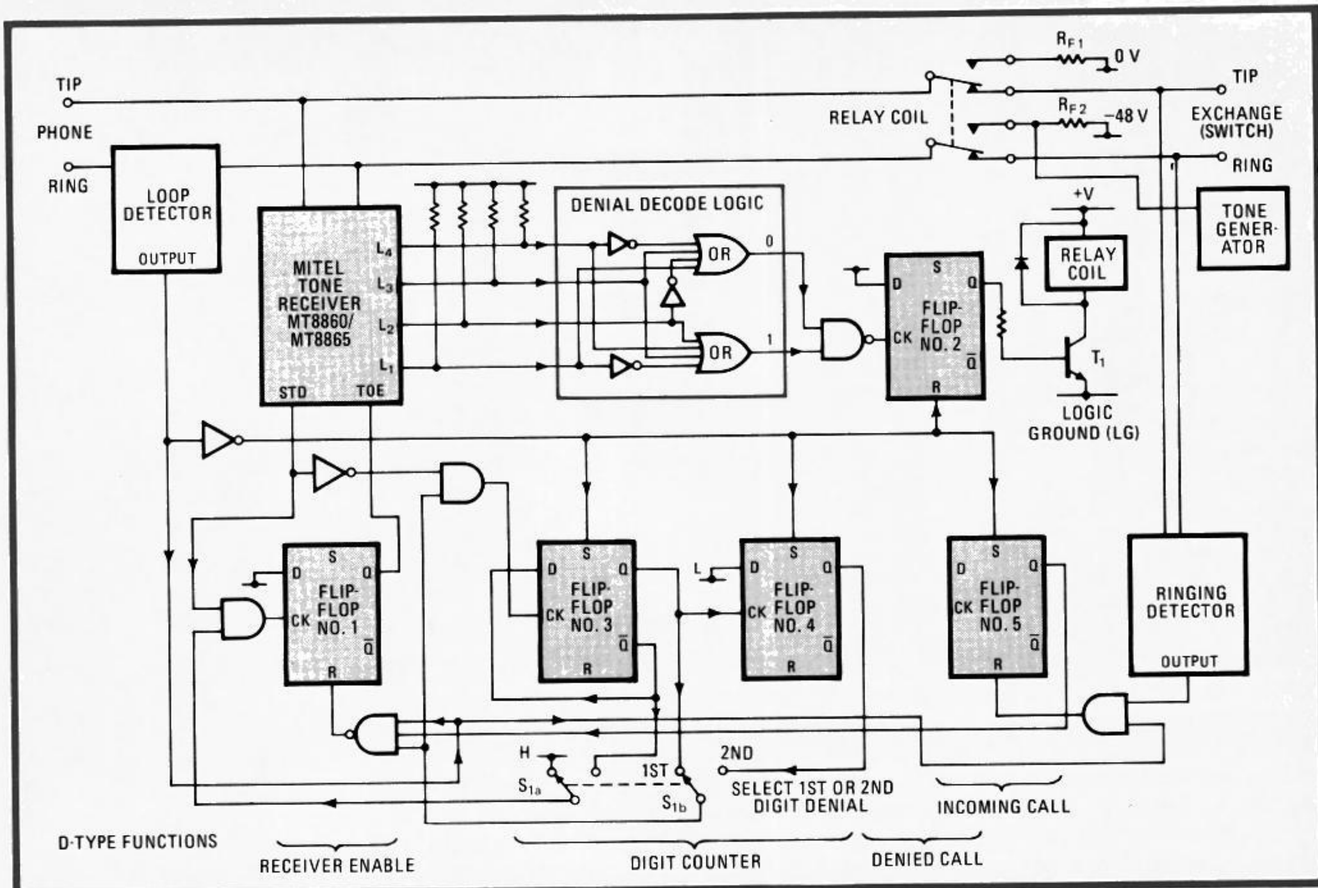
A crucial element

The most critical filter component is the operational amplifier. The bandsplit chip contains 16 of these—14 in the filters and 2 as output buffers. They are C-MOS designs consisting of two gain stages and a buffer stage to drive a 9-picofarad compensation capacitor that uses the two polysilicon levels of ISO^2-CMOS for its plates. The low gate-drain capacitance of the ISO^2-CMOS process ensures that all secondary poles are high enough in frequency not to interact with the dominant pole of this compensation capacitor.

The MT8860 decoder detects and decodes all 16 standard DTMF pairs and discriminates accurately between adjacent frequencies in both high and low groups in the presence of noise and normal voice signals.

It is this ability to function in the presence of noise that makes the 8860 superior to earlier digital detectors, which were simple period counters and depended on passive or discrete active filters to separate the DTMF signal into its constituent tones. The frequency of the tones could then be determined by measuring the time between their zero crossings. This simple technique works very well on pure single-frequency tones in the absence of noise. However, in typical applications, such ideal conditions are not met and more sophisticated algorithms must be used.

Noise originates from a variety of sources. After the DTMF signal has been processed by the bandsplit filter, the time of any given period is affected by jitter from



3. Censor. A DTMF receiver is a building block for a toll-call–denial system. Examination of the first or second digit dialed is enough to decide whether a call may be put through. The receiver is put directly in the telephone or private branch exchange to be controlled.

additive white noise, feedthrough from other frequency groups due to the finite attenuation of the bandpass filters, in-band interference tones due to distortion from incoming DTMF components and dial-tone harmonics, and impulse noise. These noise-induced errors are not insignificant. For example, white noise, feedthrough tones, or in-band interference could introduce a ±2% period modulation, so that a simple period measure would not determine the frequency of the tone accurately. Averaging several cycles—the more the better—reduces the noncorrelated effects that result from noise and interference.

Talk-off performance

Signal-to-noise performance (see "What's the twist?") is not the only parameter of interest in DTMF receivers. Voiced sounds tend to have large differences in consecutive periods due to the rich harmonic content and low frequency modulation of the pitch frequency. They can therefore have the same average period as a valid tone and be mistaken for one. Such mistakes can be prevented and talk-off performance (as it is called) improved if subintervals of the averaging time are checked to ensure that the frequency is not varying. Consequently, commercial decoders use a combined algorithm of cycle averaging and subinterval checks.

The MT8860's algorithm, for example, employs digital counting techniques to determine the frequencies of the incoming high- and low-band signals and to verify that they correspond to standard DTMF frequencies by determining the average period over a number of cycles.

To improve talk-off performance, each cycle in the low group is checked to within ±5%. This subinterval check in the low group prevents false detections of voiced sounds but would improve the performance in the high group only marginally. The high-group detection is therefore done on an average basis only, permitting die size to be reduced by 20% with no appreciable loss in receiver quality.

Some manufacturers go even further and check a number of varied subintervals, including half-cycles. But this approach imposes certain restrictions on the comparator design. For example, the need to detect both the rising and the falling edge of a signal requires low offset to be maintained to ensure a 50% duty cycle at small-signal levels. The talk-off improvement obtained by this checking of half-cycles is questionable and sacrifices signal-to-noise performance.

Three applications

Many applications of the 8865/8860 receiver are possible. A good idea of its range may be gained from the following descriptions of its use as a simple single-ended receiver, in a toll-call restrictor, and for data-communications devices.

A minimum-parts DTMF receiver using the 8860 and 8865 can be used in applications requiring only a single-ended input and no further dial-tone rejection. Both ICs

What's the twist?

DTMF receiver technology has its own jargon. Words and phrases such as talk-off, twist, signal-to-noise ratio, and dynamic range either are unique to DTMF receivers or do not have the normal definition.

Talk-off occurs when the DTMF receiver detects a tone falsely because speech or other background signals simulate and are received as DTMF tones. This parameter is difficult to measure in an absolute manner as an infinite number of tone simulations can occur. The most successful approach is the use of a standard test tape designed to contain as many near-valid tones and speech-simulated tones as practical. The most widely used standard in North America is the Mitel test tape. Fewer than 10 hits from the tape is considered very good talk-off performance.

Twist is a measure of the difference in amplitude of the two received tones. Positive twist implies that the low-group tone has a larger amplitude than the high-group tone. This is the usual case in DTMF operation since higher frequencies are attenuated by the telephone transmission lines. Negative twist is due to preemphasis of the generated high group tone that has not been normalized by transmission-line attenuation.

Signal-to-noise ratio applies only to the incoming signal and is the measure of a receiver's ability to detect a valid DTMF signal in the presence of its surrounding noise. (The noise level of the receiver itself is included in its noise figure specification.)

The dynamic range of a receiver is a measure of the range in DTMF signal amplitude that will be detected by the receiver. This is not a measure of the dynamic range of the receiver circuitry, but rather a value that is determined by setting its comparator inputs at an appropriate threshold level. The finite thresholds prevent the comparators from switching on noise or very low-level signals.

are driven from a single inexpensive crystal (Fig. 2).

The circuit takes about 30 milliseconds to receive a number. This time-to-receive is the sum of the digital detection time and the guard time. The guard time is a safety factor that prevents signal interference; it is under the control of the user and determined by the external component values (the resistors and capacitors in Fig. 2). In contrast, the user has no control over the digital detection time, as it is determined by the device's digital algorithm. It is not constant, however, but is dependent upon the state of the algorithm at the time when the tone is first applied, which tone is received, and the purity of the incoming tone.

Increasing the guard time tends to improve talk-off performance but degrades the S/N ratio of the incoming signal. It also increases the time to receive. For the circuit shown, a dynamic range of 30 dB, a twist of ±10 dB and a S/N ratio of 14 dB is obtained with readily available external resistors and capacitors. These specifications are adequate for most applications. To meet the more stringent noise requirements in mobile radio applications, the time-to-receive guard time is reduced to acquire the signal faster, and the time to signal dropout is extended to prevent distortion. An S/N ratio of 12 dB can be achieved in this way.

The data outputs L_1–L_4 of the MT8860 are three-state and are controlled by the three-state output enable (TOE) signal. When L_1–L_4 are connected to a data bus, TOE may be controlled by external circuitry or connected directly to the steering delay pin. The latter automatically enables the four outputs whenever a tone is received. In either case STD can be used to flag external circuitry to indicate that a character has been received. The STD output goes high 12 microseconds after the data has been latched into the output buffer.

Where it is desirable to receive only the characters available on a rotary-dial telephone, taking the inhibit line to a logic high inhibits detection of the additional DTMF characters (Fig. 1b). This also improves talk-off by reducing the number of detectable tones.

The basic DTMF receiver can form the heart of a toll-call restrictor. This device, not a new concept, is manufactured in the most cost-effective manner with the Mitel two-chip receiver.

A toll-call restrictor prevents the making of unauthorized calls, usually by restricting the telephone's use to local or internal private-branch-exchange calls. This is typically done by obstructing calls to numbers starting with 0 or 1 (Fig. 3). In PBX systems having an access digit for outside lines, the restrictor may have to check the second rather than the first digit of a dialed number. If it is necessary to check digits other than the first or second, this is also readily done by modifying a digit counter designed to be unaffected by subsequently transmitted or received DTMF tones.

The aim of this system is to detect denied tones as quickly as possible. To this end the guard time of the receiver is reduced. The resulting degradation in talk-off is of no concern, as the receiver is active only during transmission of the first one or two digits of outgoing calls and inactive on incoming calls.

System operation is straightforward. The tone receiver is connected across the telephone line using a differential amplifier. It is both enabled and disabled by flip-flop FF_1, which monitors call status using inputs from the loop detector, incoming-and-outgoing-call FF_5, and the digit-counter FF_3 and FF_4. When a call comes in to the telephone, ringing is detected and the system plays no part in call connection. When an outgoing call is made, the loop detector activates the receiver during the relevant digit periods.

When a valid call is made, the system disables itself until the next call. If an invalid call is attempted, the denial decode logic detects the digit 0 or 1 in the relevant digit position. This causes call denial FF_2 to activate the relay and in this way break the telephone's connection with the exchange.

Remote data links

Useful as the toll restrictor is, the chip pair has far more significance in the long run for the home and office of the future, for it can be used to set up remote data links to control microprocessors at the call recipient's site. A basic circuit to implement these remote control and remote data-entry systems is a DTMF-to-microprocessor interface. This interface can take information from the sender's DTMF keypad through either a direct link or a centrally or distributed switched communications network.

For this purpose, the keypad may be used to send coded data. The set of characters and commands sent from a standard DTMF telephone may be as simple as the 12 characters printed on the buttons. However, many other coding schemes can be implemented for specific applications. In fact, a two-digit coding scheme can easily send the entire ASCII character set.

It should also be noted that in a distributed (as opposed to a central) switching system, several pieces of receiving equipment are accessed one at a time over the same land line or radio channel. Here a DTMF receiver serves a dual purpose. As well as receiving and decoding transmitted data, it also switches the data with the aid of selective call logic. Each receiving interface on the link receives all the DTMF tones sent and decodes them while looking for its own unique access number. There is no limit to the number length so long as the selective call logic is suitably designed. A receiver decoding its own number causes a confirmation tone to be sent back to the transmitter. It then sets itself up to read subsequent tones as data. This system of switching is becoming increasingly popular as a method of selective calling of mobile, portable, and hand-held radios.

All the systems described operate only in a simplex mode with manual input. But they do not have to—given a suitable DTMF interface, the sender can be provided with a full keyboard or 16-digit hexadecimal keyboard. Furthermore, high-speed half-duplex transmission from precoded data is possible with extra DTMF interfaces.

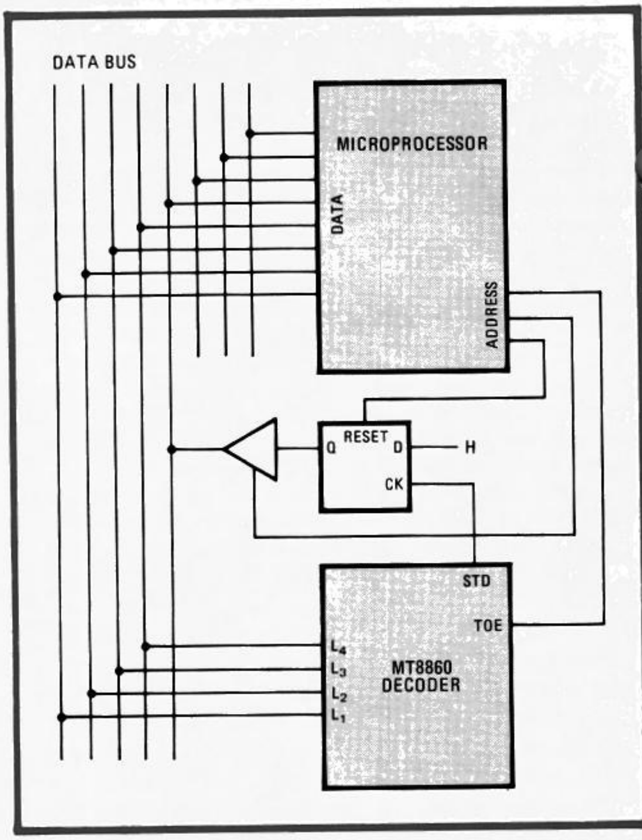
A microprocessor interface

The tone receiver readily serves as the basis of an inexpensive data-communications device. For example, a microprocessor may be remotely accessed directly from either a 16- or a 12-button pad with only the tone receiver as interface (Fig. 4). The control input/output port of the microprocessor that is used to interface with the receiver depends on the complexity of the other devices controlled.

The microprocessor is programmed to enable and check the output of the receiver latch periodically. This is set by the rising edge of the STD signal when a tone is received. If a logic high is detected on the latch output, the TOE input signal of the tone receiver is enabled and the receiver output code word is read from the data bus. TOE is then disabled and the latch is reset with an address line.

This DTMF microprocessor interface is a very basic device, but it can easily be expanded into a more useful system—for instance, a DTMF receiver interface for handling a set of up to 100 data characters and 10 command characters. The commands give the user direct control over a number of functions at the receiver without involving the main processor to which it is sending data.

In this system all 10 system commands start with *. Each of the 100 characters sent consists of two DTMF digits (using the ASCII code mentioned earlier) and is



4. Data communication. A DTMF receiver functions as part of an interface to a microprocessor at the call recipient's site. As the processor interprets the transmitted data, it provides a remote data entry capability for operating equipment or receiving data.

separated from the next character by a single-space digit #. To the user the function of the # key is similar to that of CR on a data terminal except that it is employed after every character instead of just at the end of a line. The only essential control command is CLEAR DOWN, or *1, which is used to break the connection. In this system a typical data entry from a salesman might be "Sold 22 items of product type 6 at $15.00." Abbreviated to S22 P6 $15, this is sent in the code as:

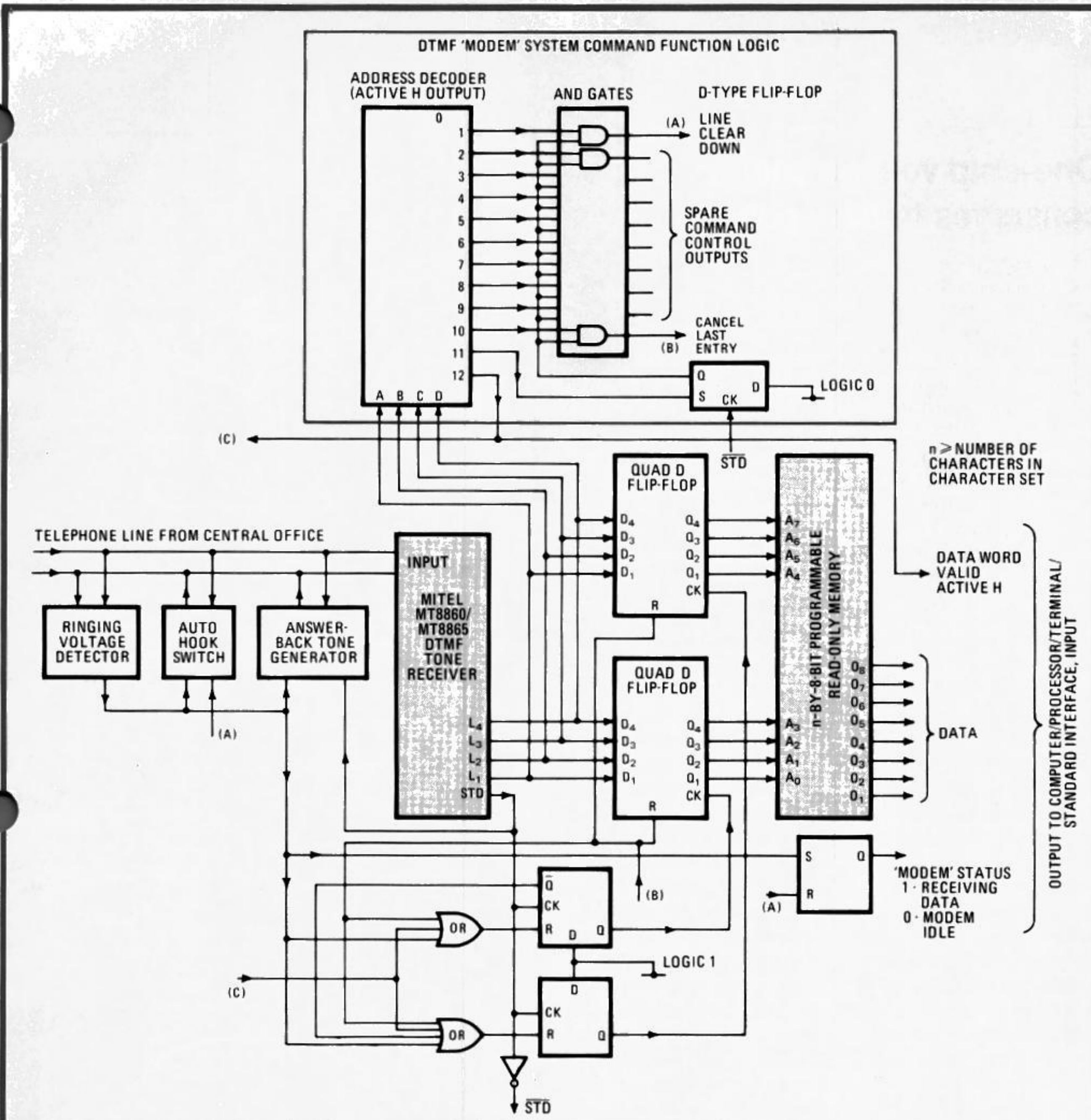
28#02#02#25#06#50#01#00#*1.

Variations on the code may be used to introduce error checking. Furthermore, if a suitable timing structure is built into the receiver and timing constraints are placed on the user, the # key may be eliminated, increasing the sending rate by as much as 50%.

Coding scheme

A circuit for receiving alphanumeric information transmitted by means of such a coding scheme is shown in Fig. 5. It employs only 2 of the 10 possible system commands, namely LINE CLEAR DOWN, to sign off at the end of a call, and CANCEL LAST ENTRY, to delete an incorrectly entered character. When decoded, the # tone indicates that the data entered is valid. Incorrectly entered data must be canceled before this character is sent. The # digit also sets the input control circuitry ready to receive a new character. The control characters themselves operate directly and are not followed by #.

The output interface is an 8-bit parallel data wo



5. On the receiving end. A DTMF receiver, control logic, and a programmable read-only memory are all that is required to accept remotely generated alphanumeric data sent from a standard DTMF telephone keypad to a recipient's terminal or microprocessor. If an existing microprocessor is used in conjunction with some additional software, it is possible to eliminate a lot of the circuit hardware.

that drives into a data bus buffer or input register of the computer or microprocessor terminal. It also sets two flag outputs that indicate the operating status of the receiver and when a new valid character is presented at the data output.

The ring detector, the hook switch, and the answer-back tone generator detect, accept, and confirm incoming calls. Each subsequent DTMF digit is decoded by the tone receiver into a 4-bit word. The 4-bit words corresponding to two successive digits are assembled in the quad latches to form an 8-bit word. This word serves as the read-only-memory address and causes the appropriate ASCII code to appear at the ROM output. The subsequent # digit decoded by the tone receiver and address decoder supplies the data-word-valid flag to the output interface. It also causes the digit sequence counters (FF_1 and FF_2) to be reset, so that they are ready for the next two digits.

The data output code of the programmable ROM can be whatever the subsequent processing equipment needs. If ASCII is required, then only 7 of the 8 bits are necessary. If retransmission through a different data-transmission system is needed, the eighth bit can be progammed to provide a parity bit. □