Application Note

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Understanding and Testing P25 Phase 2 TDMA

P25 Phase 2 is a land mobile radio standard developed by the Telecommunications Industry Association (TIA) TR8 subcommittee to meet requirements to develop a mission critical land mobile radio standard that uses the RF spectrum more efficiently. This standard meets these requirements by dividing the voice channels used for the P25 trunking voice channel into two slots, so that two simultaneous trunked voice calls can be established, using the same frequency spectrum as one voice call used in Phase 1 of P25.

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This new voice channel, using a new modulation and data rate, is able to compress the voice from a 60 ms time span into a burst of data that can fit into a time span of only 30 ms. This is accomplished by using modulation types that are capable of a higher bit rate, while still utilizing the same bandwidth as Phase 1 of P25. In addition, advancements to the vocoder enable the voice to be compressed into fewer bits than are used in the original voice channels of P25.

History of P25 Phase 2 TDMA

The history of the development of Phase 2 began early in the last decade when several different proposals for a two-slot TDMA standard were discussed in the TR8 committee. After several years of discussion the decision was made to harmonize the proposals into a single, two-slot TDMA standard. The compromises sought to find the “sweet spot” by taking the best from each of the proposals and then coming up with the best possible standard for a two-slot TDMA standard. The resulting compromise uses two different modulation schemes, one for the inbound and another for the outbound. Both of these new modulation schemes employ a faster data rate than Phase 1 of P25. The modulation schemes provide the most advantages and least number of disadvantages for the inbound and outbound signaling path. The new data rate is increased significantly from the Phase 1 P25 rate to allow for a sufficient number of bits per second to meet the requirements of dividing each channel into two time slots to support good voice reproduction. Further, the new bit rate is fast enough to provide the extra bit rate required for good forward error correction, while still having enough bits left over for signaling. The result of the harmonization of these early proposals is summarized in Table 1.

Inbound modulation	H-CPM
Outbound modulation	H-DQPSK
Bandwidth	12.5 kHz
Bit rate	12000 bps
Slot size	30 ms
Information bits per slot	320
Effective bit rate	5333.33 bps
Vocoder	Half rate Vocoder at 3600 bps

Table 1. P25 phase 2 TDMA characteristics

The physical layer for TDMA was published in July of 2009 and was followed by the TDMA Media Access Control Layer description in December of 2010. Also developed by the standards group was the two-slot TDMA Receiver Measurement Methods, which was published in August of 2011.

P25 TDMA Modulation Schemes

The two different modulation schemes for Phase 2 two-slot TDMA were selected to meet the unique needs of the outbound and inbound signaling paths. The outbound and inbound signaling paths are defined with respect to the base station. These two modulation types are H-DQPSK (Harmonized - Differential Quadrature Phase Shift Keying) and H-CPM (Harmonized - Continuous Phase Modulation).

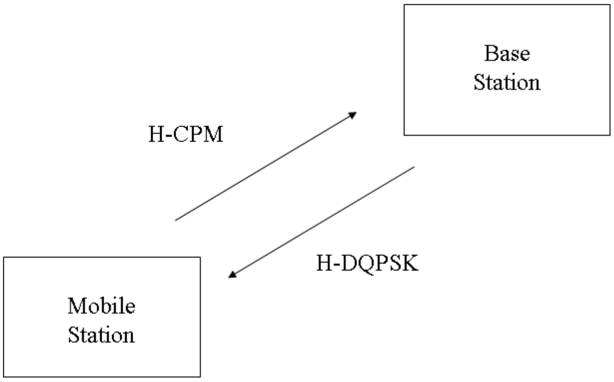


Figure 1. Mobile station and base station modulation types

The modulation selected for the base station transmit is H-DQPSK. The H-DQPSK modulation was chosen in part because of its good delay spread characteristics. Delay spread is the amount of time between two equal amplitude faded signals, such as in a simulcast environment, where the signals can arrive at different times. H-DQPSK also has a much simpler receiver implementation, making it ideal for mobile station implementation, where battery life may be important.

H-CPM was the modulation selected for use by mobile station transmitters. A critical advantage of H-CPM is that it is a non-linear modulation and therefore does not require a linear power amplifier. This was a requirement for integration into mobile stations, which required non-linear power amplifiers for current Phase 1 FDMA and FM operation. Another advantage, it is a rather simple modulation to implement and is therefore easy to add to current mobile stations. And although it is a more challenging modulation to demodulate, this should not pose a problem for base station repeaters on the receive side.

Understanding H-DQPSK Modulation

The H-DQPSK modulation is a form of $\pi/4$ DQPSK modulation. With this modulation, for each symbol (or each two bits of data), the modulation shifts the RF carrier by a multiple of $\pi/4$ radians (which is equal to 45 degrees). The phase shift can be by 45, 135, -45, or -135 degrees. The table below shows the relationship between symbols and phase shift.

Symbol Bits	Phase Shift
00_2	$\pi/4$ (45°)
01_2	$3\pi/4$ (135°)
10_2	$-\pi/4$ (-45°)
11_2	$-3\pi/4$ (-135°)

Table 2. Symbol to phase shift mapping

The phase shifts occur at a rate of 6000 shifts per second and are filtered by a type of filter called a raised cosine filter. A raised cosine filter is used for shaping phase transitions due to its ability to minimize inter symbol interference. This means that this type of filter can smooth the transition from one phase to the next, with minimal affect on the magnitude or timing of the phase shift. After filtering, the phase is very close to the same prior to filtering. Figure 2 shows the affect this filter has on the phase, showing a plot of the phase of the modulation both before and after filtering. At the end of each symbol period the phase before and after filtering is the same.

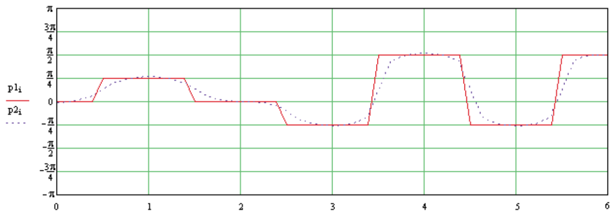


Figure 2. p1 unfiltered phases versus p2 filtered phases for 6 symbol periods

The filtering used for the harmonized DQPSK is distinguished from normal $\pi/4$ DQPSK by special filtering coefficients for the raised cosine filter. These filter coefficients for a raise cosine filter are based on two different values, the roll off factor (usually designated α) and the symbol period (T). The roll off factor is a value between 0 and 1 and determines the amount of excess bandwidth of the filter. The closer this number is to 0, the sharper the roll off. With a value of 1, the filter shape will follow the shape of a cosine wave. With a value of 0, the filter roll off is like a brick wall (very abrupt). The other value, designated T, is the symbol period. This value determines the bandwidth of the filter with the bandwidth equal to the inverse of twice the symbol period.

$$BW = \frac{1}{2T}$$

For H-DQPSK the roll-off factor (α) is set to 1. This makes the roll off of the filter follow the shape of the first 90 degrees of a cosine wave from 0 Hz to twice the bandwidth of the filter. The shape of the filter is shown in Figure 3.

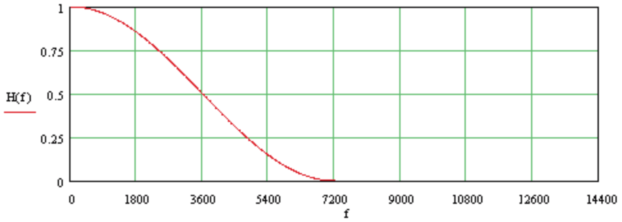


Figure 3. Harmonized DQPSK raised cosine filter

As can be seen from Figure 3, the bandwidth of the filter is 3600 Hz, which does not match what we would expect from the symbol rate. With a symbol rate of 6000, a normal raised cosine filter would have a bandwidth of 3000 Hz. So the critical differentiation between a normal and harmonized raised cosine filter is the bandwidth selected for the filter. It is this special filtering that gives the H-DQPSK the increased delay spread capability.

Understanding H-CPM Modulation

H-CPM modulation is a harmonized form of continuous phase modulation. Continuous phase modulation is a type of modulation where the phase of the carrier varies in a continuous manner while the amplitude is constant. Continuous phase modulation comes in two forms. The first form has a phase pulse filter that has a length that is shorter than the period of the symbols. (The phase pulse filter smoothes the transition from one phase to the next.) This type of filter results in the number of phase states, the phase of the modulated carrier at the start of each symbol period, to be based only on the modulation index. The second form has a phase pulse filter that has a length that is multiple periods of the symbols. This type of filter results in a greater number of phase states and is based on the modulation index, the length of the phase pulse filter, and the number of bits in the symbol. Harmonized continuous phase modulation fits into the second form.

The phase of an H-CPM modulated signal at the beginning of each symbol period is equal to the summation of the phases of all of the input symbols. All but the phases of the three most recent input symbols are scaled by half. The phases of the three most recent input symbols are scaled by the phase pulse filter.

With two bits per symbol, H-CPM input symbols have four different phase states. The phase of each symbol is based on the quaternary symbol and the modulation index (which is 1/3).

The formula that H-CPM uses for the input phase is:

phase = 2π * 1/3 * Quaternary Symbol

The symbol, quaternary symbol and corresponding phase of the input symbols are shown in Table 3.

Symbol [Input bits]	Quaternary Symbol	Phase
01_2	+3	2π (360°)
00_2	+1	$2/3\pi$ (120°)
10_2	-1	$-2/3\pi$ (-120°)
11_2	-3	-2π (-360°)

Table 3. Symbol to phase with a modulation index of 1/3 and two bits per symbol

Another way of calculating the phase of the H-CPM modulated signal at the start of each symbol period is to divide it into an equation that has two parts. The first part is a summation of the phase of all but the three newest symbols, scaled by half. This summation results in six possible phase states when the result is reduced to a value between 0 and 2π. These states are 0, $\pi/3$, $2\pi/3$, π, $4\pi/3$, and $5\pi/3$.

The second part of the equation is based on the three most recent symbols. The phase of each of these symbols is scaled by parameters from the phase pulse filter. Figure 4 shows a plot of the phase pulse filter versus symbol time. At the start of each symbol period, the newest symbol is scaled by the value corresponding to symbol 1 (about 0.005), the second by the value corresponding to symbol 2 (0.25) and the third most recent value is scaled by the value corresponding to 3 (about 0.495).

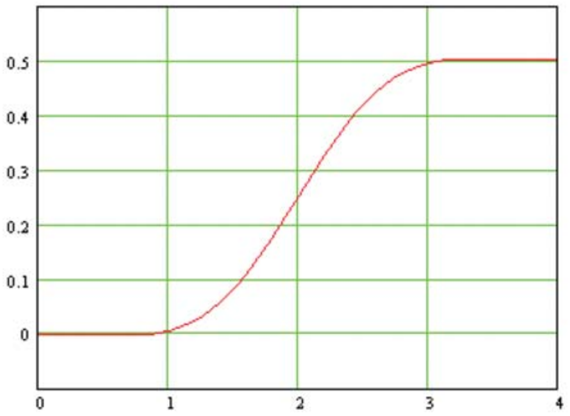


Figure 4. Phase pulse filter plotted versus symbol time

Each of these three symbol phases takes on one of four unique values after being scaled by the phase pulse filter. The combination of four unique values at three points, calculated as 4 to the 3rd power, equates to 64. Therefore the summation of these three scaled phases has 64 phase states. The combination of the first (6 phase states) and second (64 phase states) part of the equations results in a total of 384 possible phase states (6 X 64).

Although 384 is the possible number of phase states, some of the states are very close to being the same phase and some of the phases repeat. Because of the shape of the phase pulse filter, the 64 phase states from the three most recent symbols can actually be reduced to just four phase groupings that are very close to the same value. These values are $\pi/2$, $\pi/6$, $11\pi/6$, and $3\pi/2$. When you sum these four values with the six values from the first part of the equations you come up with twenty-four values. This is shown in Table 4. The first row contains the six possible phase states that results from all but the 3 most recent symbols. The first column contains the four phases that are a result of the newest three symbols. The other locations in the table are the result of adding the first column to the first row. These are the twenty-four phase states.

	0	$\pi/3$	$2\pi/3$	π	$4\pi/3$	$5\pi/3$
$\pi/2$	$\pi/2$	$5\pi/6$	$7\pi/6$	$3\pi/2$	$11\pi/6$	$\pi/6$
$\pi/6$	$\pi/6$	$\pi/2$	$5\pi/6$	$7\pi/6$	$3\pi/2$	$11\pi/6$
$11\pi/6$	$11\pi/6$	$\pi/6$	$\pi/2$	$5\pi/6$	$7\pi/6$	$3\pi/2$
$3\pi/2$	$3\pi/2$	$11\pi/6$	$\pi/6$	$\pi/2$	$5\pi/6$	$7\pi/6$

Table 4. Possible phase states

Even these twenty-four values are not unique; you can see that some of these phase states repeat, so the minimized phase state list is $\pi/6$, $\pi/2$, $5\pi/6$, $7\pi/6$, $3\pi/2$, and $11\pi/6$. It is illustrative to show these points plotted on the unit circle. They are shown below in Figure 5.

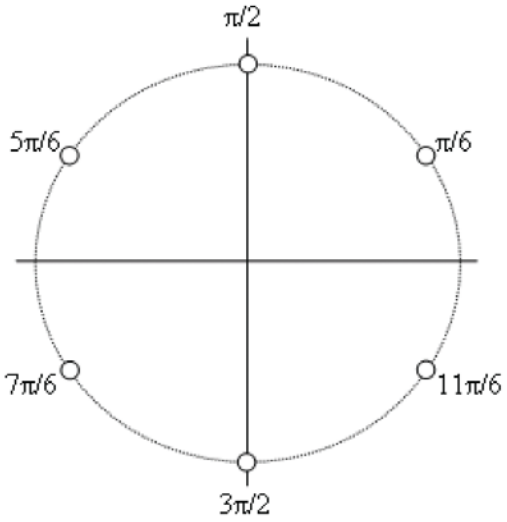


Figure 5. H-CPM phase states shown on the unit circle

As we stated, these are the phase groupings, and the phase positions do not fall exactly on these six states, but in actuality look like Figure 6. In this illustration, the large black circle is the plot of the phase and magnitude of the modulated signal, where the small red circles mark the phase and magnitude of the modulated signal at the start of each new symbol period. During the transition of the signal from one symbol to the next, the phase varies continuously, while the magnitude of the modulated signal remains constant.

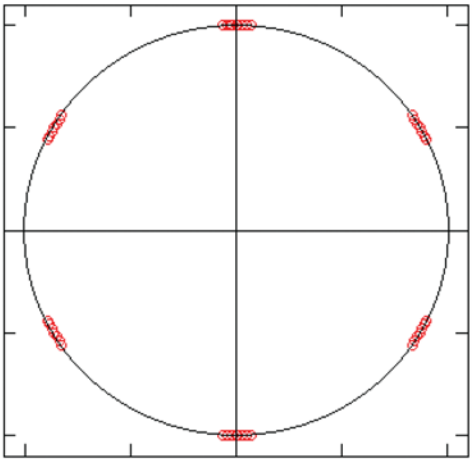


Figure 6. Plot of phase and magnitude for H-CPM

Another way to look at this modulation is shown in Figure 7 where the phase of an H-CPM signal is plotted over time. Each vertical position of the grid is the start of the next symbol. You can see from this plot that the phase varies continuously and smoothly from one symbol to the next.

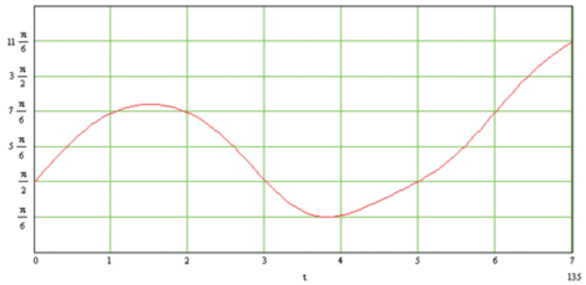


Figure 7. Phase plot versus symbol for H-CPM

Often this type of modulation is analyzed by measuring the phase change over a symbol period. With six phase states the possible number of phase changes are 7 [-π, - 2π/3, -π/3, 0, π/3, 2π/3, π], including a phase change of 0. With H-DQPSK modulation, there is a one to one correspondence between the phase change over a symbol period and the two bits that generated the modulation. H-CPM does not have this correspondence of symbol bits to phase shift. The amount of phase change is always due to two successive symbols. The following table shows the relationship between successive symbols and the resulting phase change.

Successive Symbols	Phase Change
01_2 01_2	π(180°)
00_2 01_2 or 01_2 00_2	2π/3 (120°)
10_2 01_2 or 00_2 00_2 or 01_2 10_2	π/3 (60°)
11_2 01_2 or 10_2 00_2 or 00_2 10_2 or 01_2 11_2	0
11_2 00_2 or 10_2 10_2 or 00_2 11_2	- π/3 (-60°)
11_2 10_2 or 10_2 11_2	-2π/3 (-120°)
11_2 11_2	-π (-180°)

Table 5. Phase change table

As can be seen from this table, there is not a one to one relationship between successive symbols and the amount of phase change. For example, the successive symbols 01_2 00_2 or 00_2 01_2 would lead to a phase change of 2π/3 radians. Because of this a simple demodulation process is not possible, one that only looks at the phase change over a symbol period. Instead, a process of finding the most likely sequence of symbols that track the phase of the received signal is used to demodulate the symbols.

Testing P25 Phase 2

Although the modulation for H-CPM and H-DQPSK are different, the same measurements are required to be performed on both modulation types. These measurements insure that the modulation is performing optimally, so that the inbound and outbound signaling paths are maximized. The measurements for both of these modulation types are also similar to those required for the C4FM Phase 1 modulation. The key measurements for P25 Phase 2 are:

- Modulation fidelity
- Symbol deviation
- RF frequency error
- Symbol rate accuracy
- Receiver bit error rate
- RF output power over the burst

These measurements are important for verifying the correct operation of a P25 Phase 2 radio.

Modulation Fidelity and Symbol Deviation

Modulation Fidelity is a measurement of the degree of closeness that the transmitted modulation matches the ideal theoretical modulation. Even though both of the modulations employed in Phase 2 of P25 are phase based modulation, the measurements used to evaluate the modulation are based on the FM deviation of the modulation measured through an integrate and dump filter. An integrate and dump filter is simply a filter that averages samples of the demodulated signal over the symbol period of the modulation. This is the same as the measurements used to evaluate the Phase 1 C4FM modulated signal.

The reason that frequency deviation based measurements can be used to evaluate this modulation is because the frequency deviation of a phase modulated signal is directly related to the rate of change of the phase. For example, a delta phase change of 180 degrees over a symbol period for H-CPM is equal to an average frequency deviation of 3000 Hz. The formula for this is very simple. It is:

(Delta phase/360°)* symbol rate

Or for this example:

(180°/360°)* 6000 Hz = 3000 Hz

So this measurement is made by FM demodulating the signal from the radio, and after filtering, comparing the deviation, at symbol time, with the expected deviation. This measurement is divided into two parameters:

1. The RMS of the deviation error
2. The average normalized deviation referenced to the maximum deviation symbol

The RMS of the deviation error is commonly referred to as Modulation Fidelity. This is the RMS of the difference between the received deviation and the average deviation of the symbol. The Symbol Deviation measurement is the average normalized deviation at each of the symbol points. The deviation is normalized by dividing the deviation for each of the deviation states by the expected deviation. The normalized values are averaged and then multiplied by 2250 for H-DQPSK and by 3000 for H-CPM to reference it to the maximum deviation point.

At symbol time the FM deviation of the H-DQPSK modulated signal, through the integrate and dump filter, takes on four different states. These four states correspond to the four different phase shifts of the signal that occur during a symbol period. Table 6 shows the relationship between the phase shift and the frequency deviation.

Phase Shift	Frequency Deviation (Hz)
3π/4 (135°)	2250
π/4 (45°)	750
-π/4 (-45°)	-750
-3π/4 (-135°)	-2250

Table 6. Phase shift/frequency deviation relationship for H-DQPSK

For H-CPM modulation, the FM deviation takes on seven different states. This would correspond to the seven different phase shifts that can occur over a symbol period. The relationship between the phase shift over a symbol period and the frequency deviation measured at the symbol point can be seen in Table 7.

Phase Shift	Frequency Deviation (Hz)
π (180º)	3000
2π/3 (120º)	2000
π/3 (60º)	1000
(0°)	0
-π/3 (-60º)	-1000
-2π/3 (-120º)	-2000
-π (-180º)	-3000

Table 7. Phase shift/frequency deviation relationship for H-CPM

There are several different ways of graphically analyzing the modulation fidelity and symbol deviation of these two types of modulation. Three methods that are employed by the Aeroflex 3920 are:

1. Constellation diagram
2. Distribution diagram
3. Eye diagram

The constellation diagram for H-DQPSK is shown in Figure 8. This diagram shows a plot of the frequency deviation of the demodulated signal. This is the frequency deviation measured at each symbol point. This diagram is a horizontal line graph and has no vertical units. From this diagram you can see that the frequency deviation is always very close to the four deviation points that were identified in Table 6. The green circles indicate the bulls-eye location for the deviation but are not indicative of any pass/fail requirements.

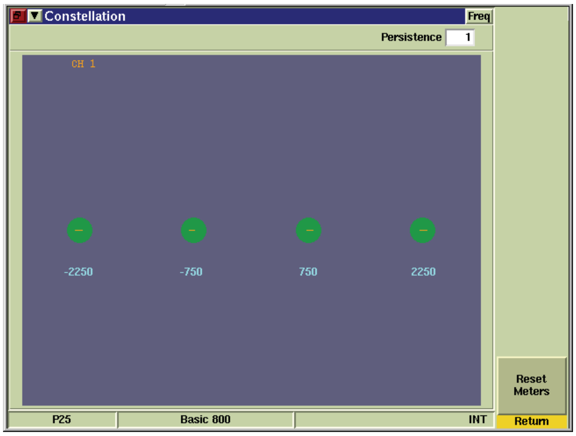


Figure 8. H-DQPSK constellation

Another diagram that is even more illustrative of the modulation is the distribution diagram. Figure 9 shows the distribution diagram for H-CPM. This diagram plots the frequency deviation at the symbol point versus the percentage of occurrence. This diagram not only shows the frequency deviation, as the constellation diagram does, but also indicates the relative number of occurrences of each deviation. From this diagram, for example, the user can see that the frequency deviation of 0 Hz occurs more often than the other deviations. This corresponds with the relationship between symbol sequences and phase changes shown in Table 5, where the phase change of 0 correlates to the largest combination of successive symbols. The user can also see, from the shape of the distribution for each frequency deviation state, that the points are distributed around the ideal location indicated by the dashed line. The filtering used for H-CPM is the reason that the distribution of each frequency deviation varies slightly from the dashed line and is not indicative of an inferior signal.

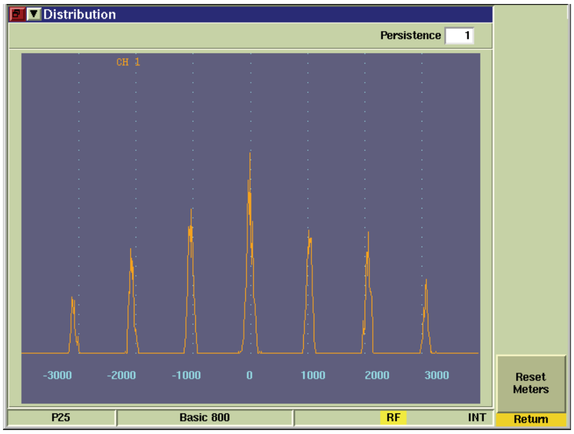
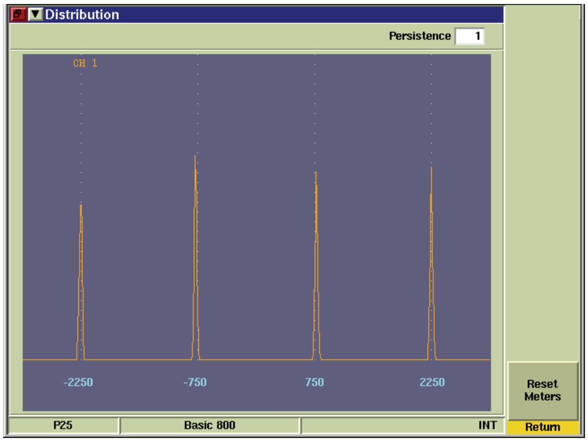


Figure 9. Distribution diagram for H-CPM

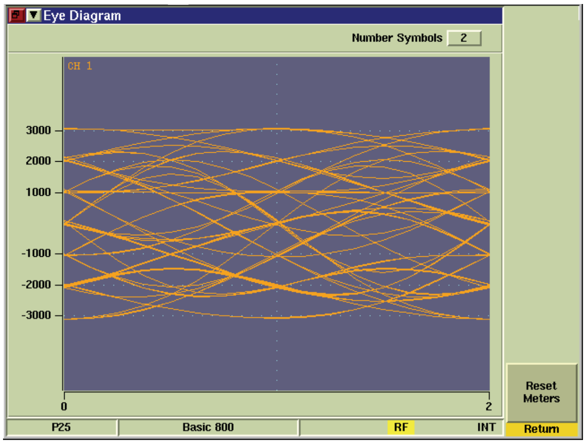
The ideal H-DQPSK modulation, as illustrated in Figure10, has a distribution diagram that is very narrow for each deviation state.



Persistence 1

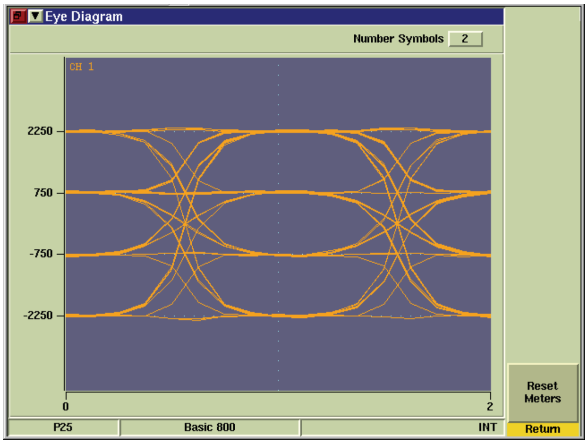
Figure 10. Distribution diagram for H-DQPSK

Up to this point the diagrams have focused only on the frequency deviation "at the symbol point". The eye diagram provides information on the deviation at the symbol point and also all the points in between. Figure 11 shows the eye diagram for H-CPM and Figure 12 shows the eye diagram for H-DQPSK. The start, middle, and end of these two diagrams are referred to as the symbol point. This is point in the modulation that the frequency deviation is measured for purposes of determining the modulation fidelity and symbol deviation. All points in-between illustrate the path that the frequency deviation takes when transitioning from one symbol to the next. As can be seen from these two diagrams, the H-CPM modulation very smoothly transitions from one deviation to the next, while the H-DQPSK modulation transitions to a deviation and then holds that deviation for almost half of the symbol time. It is interesting to observe the differences while also understanding that the H-CPM modulation holds a constant envelope, while the H-DQPSK has an amplitude modulation component.



Number Symbols 2

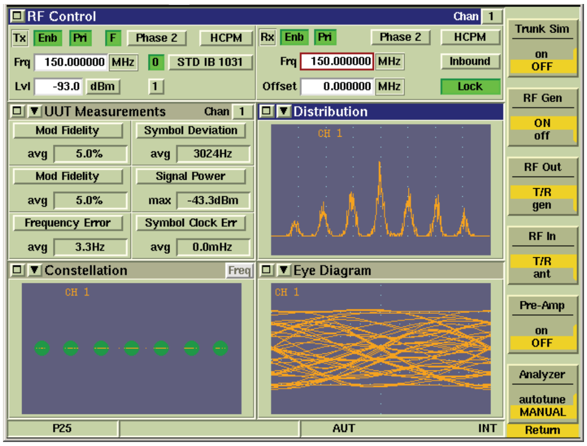
Figure 11. Eye diagram of H-CPM



Number Symbols 2

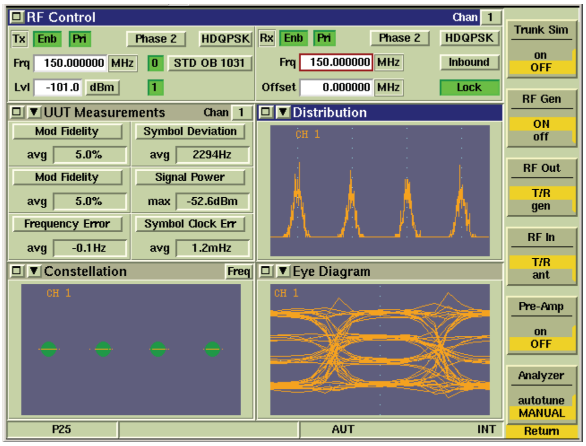
Figure 12. Eye diagram of H-DQPSK

The Phase 2 standard specifies that the modulation fidelity should be 5% or less. The 3920 screen shots shown in Figures 13 and 14 illustrate what this looks like on these three diagrams for H-CPM and H-DQPSK respectively.



Chan 1
Tx: Phase 2, HCPM
Frq 150.000000 MHz, 0, STD IB 1031
Lvl -93.0 dBm, 1
Rx: Phase 2, HCPM
Frq 150.000000 MHz, Inbound
Offset 0.000000 MHz
UUT Measurements Chan 1
Mod Fidelity avg 5.0%
Symbol Deviation avg 3024Hz
Mod Fidelity avg 5.0%
Signal Power max -43.3dBm
Frequency Error avg 3.3Hz
Symbol Clock Err avg 0.0mHz

Figure 13. 5% Modulation fidelity diagrams for H-CPM



Chan 1
Tx: Phase 2, HDQPSK
Frq 150.000000 MHz, 0, STD OB 1031
Lvl -101.0 dBm, 1
Rx: Phase 2, HDQPSK
Frq 150.000000 MHz, Inbound
Offset 0.000000 MHz
UUT Measurements Chan 1
Mod Fidelity avg 5.0%
Symbol Deviation avg 2294Hz
Mod Fidelity avg 5.0%
Signal Power max -52.6dBm
Frequency Error avg -0.1Hz
Symbol Clock Err avg 1.2mHz

Figure 14. 5% Modulation fidelity diagrams for H-DQPSK

You can see from these screens shots that with modulation fidelity of 5% the frequency deviation delta between states is reduced. This has an impact on the range of inbound or outbound signaling paths, as it takes a smaller amount of noise or interference, before the deviation state of a symbol can be indeterminate.

RF Frequency Error

The RF frequency error of a modulated signal is also a component of the modulation fidelity measurement. A modulated signal may naturally deviate either more in a positive or negative amount, due to the bit symbol sequence responsible for the modulation. There is not necessarily an equal balance between the positive and negative frequency deviation. Therefore a normal RF frequency counter would probably make an inaccurate measurement of a modulated carrier, unless the data stream modulating the carrier is a random data sequence. The frequency error meter must follow the modulation and then determine the average positive or negative amount of frequency deviation from the expected. The 3920 implements this as part of the modulation fidelity measurement and displays it in the Frequency Error Meter. This enables the measurement to accurately be made on P25 Phase 2 modulated signals. The specification for frequency error varies by band and can be seen in Table 8.

Assigned Frequency (MHz)	Mobile and Portable	Base Station
Below 100	5.0	2.5
From 138 to 174	2.5	1.5
From 406 to 512	2.0	0.5
From 769 to 806	0.4_1 1.5_2	0.1
From 806 to 869	1.5	0.15
From 896 to 941	1.5	0.1
Notes: $_1$ When AFC is locked to the base station. $_2$ When AFC is not locked to the base station.		

Table 8. Maximum frequency error (PPM) from TIA 102.CCAB

Symbol Clock Error

The symbol rate for both modulation types is 6000 symbols per second. Errors in the symbol rate of a transmitted signal can lead to errors in the demodulation of the signal and can result in a higher bit error rate, reducing the range of operation. The 3920 symbol clock error meter measures the accuracy of the symbol rate in either mHz (mill hertz) or in PPM. The P25 Phase 2 specification for symbol rate accuracy is 10 PPM (which is 60 mHz).

Receiver Bit Error Rate (BER)

The performance of the receiver of a P25 Phase 2 radio can be determined by the number of bit errors out of the receiver of the radio. This measurement is performed by generating a standard signal, which includes a specified bit pattern into the receiver of the radio under test. This measurement is generally made with the radio in test mode, reporting the BER results of a comparison between the received and expected bit pattern. The P25 standard specifies the bit pattern that should be used for this test. The receiver sensitivity test is made by generating a 1031 Hz tone test pattern, at the receiver sensitivity level, and then measuring the bit error rate. At this level the bit error rate should be 5% or less. With the 3920 the STD IB1031 (for H-CPM) or STD OB 1031 (for H-DQPSK) pattern should be selected from the list of standard patterns. The receiver sensitivity for P25 Phase 2 radios varies by the class of radio but can be seen in Table 9.

Radio Application	Mobile	Portable	Base Station
Class A	-116 dBm	-116 dBm	-116 dBm
Class B	-113 dBm	-113 dBm	-113 dBm

Table 9. Sensitivity of P25 phase 2 mobiles, portables and base stations from TIA-102.CCAB

RF Output Power Over the Burst

With P25 Phase 2 the power of the signal is specified over the TDMA timeslot. For an inbound H-CPM modulated signal this measurement must be made during a 24 ms duration of the 28 ms burst, so that the ramp up, ramp down and settling time do not affect the power measurement. The signal from a base station is continuous, but the H-DQPSK modulation is a complex modulation, with variations in amplitude and phase. The H-DQPSK power measurement must be taken with a power meter capable of measuring AM power. The 3920 power meters take both the burst nature of the H-CPM inbound signal and the amplitude modulated nature of the H-DQPSK outbound signal into account when taking this measurement.

The manufacturer specifies the RF power requirements of the radio, although it should not exceed by more than 20% the rating for which the equipment has been type accepted by the FCC. In addition, the following requirements exist for equipment designed to operation at 775-776/805-806 MHz and 769-775/799-805 MHz.

Station Type	Maximum Output Power
Mobile, and Control	30 Watts
Portable (hand-held)	3 Watts

Table 10. Power requirements of mobile and portables

Conclusion

It is important for those testing and maintaining P25 Phase 2 radios to understand the new modulation types so that they can insure their radios are operating at the highest level possible. Optimum transmitter and receiver operation is critical to mission critical communication and it is imperative that they are properly tested and maintained to the highest standard. The radio technician must understand what is being tested, the best method to test and the standards which the testing must insure.

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