A ROBUST DIGITAL WIRELESS LINK FOR TACTICAL UAV'S

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ABSTRACT

Tactical unmanned aerial vehicles (UAV's) can deliver real-time battlefield video directly to the soldier providing unprecedented situational awareness. The video communications system must be compact, lightweight, secure, and easy to deploy without a complicated ground station. Pacific Microwave Research, Inc. is developing a system capable of providing reliable and secure video communications to handheld terminals throughout the theater. PMR's Coded Orthogonal Frequency Division Multiplex (COFDM) video transmission system is designed for tactical video transmission in battlefield or Military Operations in Urban Terrain (MOUT) environments. Using digital modulation coding, the system provides a very robust link in the mobile environment.

KEYWORDS

Airborne Video, Digital Microwave Transmission, COFDM, Non-Line-of-Sight Wireless Video, Tactical UAV.

INTRODUCTION

Military and Law Enforcement users of analog microwave video links have long contended with the debilitating effects of multipath on the performance of analog links. Multipath occurs when a radio frequency signal is reflected off a surface (or multiple surfaces) and arrives at the receiver antenna at some later time. These time-delayed signals combine in such a manner as to create non-linear response across the channel of interest. As a result, certain frequencies within the received bandwidth are reduced in level while others are increased. When this effect occurs at critical points with the transmission baseband (video synchronizing pulses, for example) the video signal will roll and tear across the screen making the image data unusable. Multipath is an environmental problem that is particularly difficult to avoid.

Coded Orthogonal Frequency Division Multiplex (COFDM) is a multi-carrier digital transmission scheme that consists of approximately 2000 radio frequency carriers contained within an 8 MHz bandwidth. Each carrier can be modulated using QPSK, or16-QAM, (depending on data throughput requirements and channel response) to form an aggregate data transmission rate between 5 Mb/s to 20 Mb/s. Using forward error correction and interleaving techniques (this is the Coded part of COFDM), the data is coded onto the multi-carrier system and transmitted at the desired microwave frequency. If an adverse channel response should occur as a result of multipath reflections, the forward error correction coding scheme is able to recover the data from the lost carriers and reconstruct the proper video image at the receiver. COFDM is able to provide a high immunity to multipath and make possible true mobile high-bandwidth communications with simple antennas. This opens the door to a wide range of first responder and tactical UAV applications.

Non-Line-of-Sight Microwave Digital Microwave Transmission for Tactical UAV's

Small tactical UAV's can provide realtime battlefield imagery from on-board visual and thermal sensors direct to soldiers on the ground. In order for this scenario to operate effectively, ground troops cannot be bothered with the requirement to erect tracking antennas and an elaborate ground station to receive aerial reconnaissance imagery. A system that uses lightweight portable antennas (either stationary or mobile) would better suit the mission profile of a fast moving tactical response unit. Such a hardware configuration, however, would result in poor performance in the dynamic battlefield environment if it is a conventional analog microwave video transmission system. The solution to reliable and secure wireless video communications in the tactical UAV environment is COFDM digital transmission.

The unavoidable problem of multipath in analog systems can make video collection difficult, and in some cases, impossible in the tactical environment. Digital transmission differs substantially from analog by incorporating both digital video compression and transmission techniques. Chief among the benefits of this technology is its ability to deliver reliable video imagery in an environment that is rife with multipath. This facilitates rapid deployment systems, mobile surveillance, and high-quality tactical video collection in urban environments. In addition, because the system operates in the digital domain, scrambling techniques can be implemented to provide secure links that exceeds the level of security (immunity to intercept) possible with analog links by many orders of magnitude.

Digital video transmission technology holds the promise of offering tactical video from a UAV platform that is reliable, robust, and free of the multitude of problems that frustrate that effort when analog transmission is employed. Airborne digital video can be delivered to simple portable and mobile ground stations to provide realtime situational awareness in the tactical environment. Since COFDM digital transmission can provide true non-line-of-sight functionality, both battlefield and military operations in urban terrain (MOUT) requiring airborne video intelligence may be effectively supported from a tactical UAV with a visual or thermal sensor.

MULTIPATH

Typical line-of-sight video links use large tracking dish antennas. This is not the way tactical video collection systems are deployed. Tactical video applications require a ground station that is portable and simple to set-up and operate. In some applications the receive system may be mobile during the collection activity. As a result, large directional antennas and tracking systems are not well suited to the application. The most desirable antenna configuration for tactical operations is a low to medium gain omni-directional antenna. This allows the ground station or individual soldier to move freely within the environment without the concern of maintaining a track on the support tactical UAV.

Unfortunately, an installation configured in such a manner would be plagued by multipath reflections and yield poor results using analog technology.

Multipath is problematic in tactical video collection. Signals reflect off the ground, trees, vehicles, buildings, and thousands of other surfaces in the environment. When this happens, the desired (or direct) signal is not the only one that arrives at the receiver. The reflected signals also arrive at the receiver at some point later in time. Therefore, when the energy travels a greater distance to arrive at the same destination, it must arrive later in time. This time delay degrades the analog video signal. The direct wave is shown as D_1 in Figure 1, while the reflected wave is shown in its component parts as D_2 and D_3. It is important to note that only a single case of multipath reflection is shown. In real-world applications, thousands of reflected signals conspire to diminish the quality and reliability of the analog link.

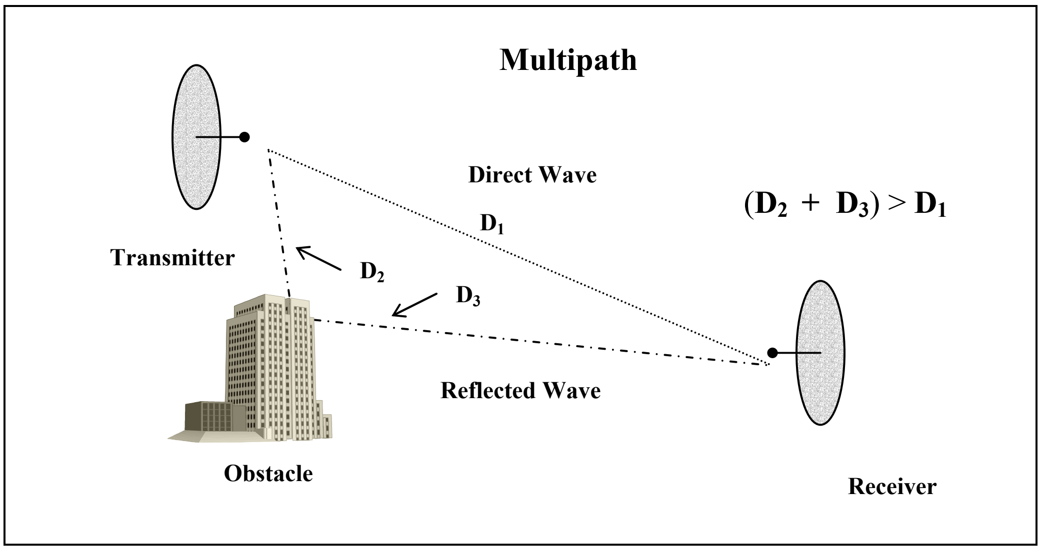

Fig. 1. Graphic Representation of Multipath

Short time-delay reflections cause the transmitted analog picture to break-up and roll. To understand how multipath fading effects the transmission channel refer to Figure 2. This graph represents the signal characteristic of an ideal transmission channel. The signal amplitude (or level) is constant across the bandwidth (frequency of operation) of the transmission channel. This is what might be expected with a direct coax connection or parabolic dish antennas in a clear line-of-sight environment.

When a transmitted radio frequency signal reflects off surfaces in a multipath environment, the energy arriving at the receiver is no longer equal across the desired bandwidth due to phase cancellations. The phenomena results in loss of signal at certain frequencies within the channel. A multipath channel response might resemble that shown in Figure 3. The deep nulls in the response graph represent a significant loss of signal at these frequencies.

Channel response will change as it is influenced by the unique multipath conditions in the tactical environment. This is why slight changes in antenna position at the transmitter or receiver locations can have such a profound impact on the quality of an analog link. Since it is difficult or impossible

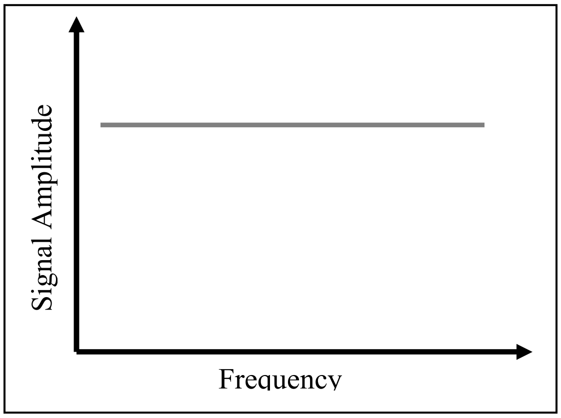

Fig. 2. Response of an Ideal Transmission Channel

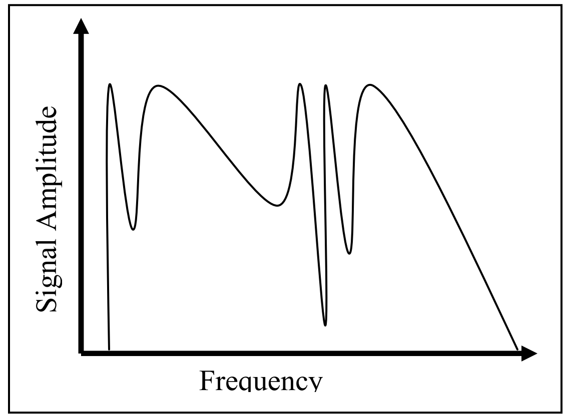

Fig. 3. Response of Multipath Channel

to control the reflective surfaces in the environment, multipath is often a problem with only a temporary solution. Movement of objects in range of the transmission system (people, vehicles, equipment, etc.) will result in a change in the destructive effects of multipath. This is one of the primary reasons that make it so difficult to maintain the quality of an analog tactical surveillance link over time.

Therefore, multipath in an analog system results in both modulation phase distortion and loss of signal. As a result, the artifacts of multipath limit the practical applications of analog technology for tactical deployment. Digital COFDM modulation overcomes most of these problems making possible a variety of non-line-of-sight (NLOS) tactical video applications.

THE TECHNOLOGIES BEHIND DIGITAL VIDEO TRANSMISSION

Digital video transmission technology provides a significant advantage over analog technology due largely to the modulation technique. It is the modulation scheme that results in a reliable and robust link that is virtually immune to the effects of multipath. Digital modulation makes it possible to realize NLOS wireless video transmission. Digital video transmission combines two important technologies to deliver high-quality video, audio, and data signals in the microwave frequency bands. These primary technologies are MPEG-2 and COFDM. MPEG-2 is a video compression technique and COFDM (Coded Orthogonal Frequency Division Multiplex) is a modulation coding technique. Together, with advanced error correction schemes, they comprise digital video transmission.

MPEG-2 VIDEO COMPRESSION

Most video cameras today produce a compliant analog video signal. In North America cameras conform to the National Television Systems Committee (NTSC) standard. In Europe, and many other parts of the world, the International Radio Consultative Committee (CCIR) standard is recognized. The CCIR standard is commonly known as PAL. Before an analog video signal can be transmitted over a digital wireless link it must first be digitized. Digitizing an NTSC video signal results in a data stream at 168 Mb/s. This data rate is far too large for digital transmission in a reasonable bandwidth. To reduce the bandwidth (data rate) the data must be compressed. This is accomplished using a motion prediction coding technique known as MPEG-2. MPEG-2 compression can reduce an NTSC data stream from 168 Mb/s to 2 – 3 Mb/s. The result is a high-definition digital video signal at a data rate that is suitable for transmission using COFDM.

Pacific Microwave Research has implemented a low-latency coding derivative of the MPEG-2 standard to reduce the processing delay experienced between the source coder at the transmitter and decoder at the receiver. This is accomplished eliminating the bi-directional frame (B-frame) and distributing inter-frame (I-frame) image data across a series of predictive frames (P-frame) instead of transmitting the I-frame data all at the same time. As a result, it is easier to pilot a remote controlled vehicle using an on-board camera as a reference since the image latency is reduced to less than 50 ms.

CODED ORTHOGONAL FREQUENCY DIVISION MULITPLEX

COFDM is a complex modulation technique designed to transmit digital data and provide substantial immunity to multipath artifacts. The technique was developed to serve as a missile telemetry transmission system as a result of the problems encountered when receiving data from a moving object in a multipath environment. At the time the technique was developed, technology was not mature enough for a practical system to be built. Today's technology, including large Field Programmable Gate Arrays, high-speed microprocessors, and Direct Digital Synthesis makes COFDM a practical modulation scheme.

Unlike conventional analog transmission that utilizes a single radio frequency carrier to transmit video information, COFDM uses approximately 2000 carriers to transmit the information. Since the data is spread over 2000 carriers instead of just one, signal cancellation due to multipath reflections have significantly less impact on the quality of the signal. Coupled with forward error correction, the signal can be reconstructed and the data extracted even under the most adverse transmission conditions.

The 2000 data carriers are spread across an occupied spectrum of only 8 MHz. Reduction of the system noise bandwidth as compared to an analog video transmitter requiring 16 MHz of occupied bandwidth provides system gain. The carriers may be modulated using quadrature phase shift keying (QPSK) up to 64-QAM. Fixed links can take advantage of high-order modulation to pass up to 32 Mb/s. However, tactical links operate best using QPSK modulation because it is the most robust format with respect to multipath performance. For practical purposes, it is reasonable to limit high-order modulation to 16-QAM for tactical deployment.

If multipath should corrupt a handful of carriers, the forward error correction (FEC) will predict what the data should have been and reconstruct the data. In general, the modulation technology results in at least a 10 dB improvement when compared to analog transmission technology. While this improvement can be quantified at 10 dB on the bench, the actual improvement experienced can be significantly greater in real-world applications when various levels of multipath conspire to degrade the analog signal. A difference in 10 dB is equivalent to comparing the performance of a 0.1W digital transmitter to a 1.0W analog transmitter. Of course, the resultant performance differential is manifest as more than simply a difference in power levels. The ability to resist multipath means consistently good video images up until no further energy is available for the link to operate properly. In comparison, as an analog signal degrades the picture will become noisy and may tear or roll.

A simple path calculation for a 1 W system at 2300 MHz indicates that an analog system will yield a reliable signal over a line-of-sight path at up to 2 miles. A digital system will provide reliable signals with a 1 W transmitter at 2300 MHz at up to 6.5 miles! The advantage of COFDM is that the picture will be good using the digital system almost anywhere within the maximum calculated range while the analog signal is unpredictable within its maximum calculated range due to the effects of multipath.

For most tactical UAV applications the actual range the system will operate over is not as important as how well the system performs over a short to medium range in a difficult environment. While an analog system may have the potential to operate over a predicted line-of-sight range of over one mile, it may be completely useless when the transmitter and receiver are separated by only 50 ft. because of the effects of multipath. In most cases, a digital link will give exceptionally good results until the receiver has inadequate signal input. This independence from the environment makes COFDM digital technology the best choice for reliable tactical applications.

A digital COFDM signal occupies half of the spectrum that an analog signal does. This means that more signals can be used within any given bandwidth as compared to using analog transmission. This is important because spectrum is quickly becoming a scarce resource. Pressure from commercial interests is forcing the government to transfer microwave spectrum from government use (military and federal law enforcement) to commercial use to satisfy the demands of new public telecommunications technologies. The spectrum efficiency of digital transmission enables agencies to do more with less.

Additionally, the carrier level of the digital system is lower than that of the analog level in the graphic to illustrate the performance advantage discussed above. As a general rule, it can be assumed that approximately 10 times less power may be transmitted using digital technology as compared to analog technology for a given range. This also means that the radio frequency signature is lower making detection by an adversary much more difficult.

It is the mathematically derived spacing of the carriers that diminishes the negative effects of multipath. Unwanted reflections (or echoes) are time delayed as described above. As a result, the reflected signals fall between the desired carriers in what is essentially unused inter-carrier spectrum (guard interval). The demodulator performs a Fast Fourier Transform (FFT) and the energy present as a result of the reflections is processed out leaving only the data on the desired carriers. It is the amount of carrier spacing in a COFDM system that determines the range performance of the system in a multipath environment. Greater carrier spacing accommodates longer echo delays at the expense of requiring more spectrum for a given number of carriers. Carrier guard interval is expressed as a fraction of the symbol rate of an individual carrier.

The carriers in a COFDM system are positioned such that the energy contained in the sin(x)/(x) response of each carrier is aligned with the adjacent orthogonal carrier as shown in Figure 4. When integrated, the energy from each carrier yields a zero-sum resulting in the creation of the inter-carrier guardband. This phase relationship ensures that the carriers do not interfere with each other. While

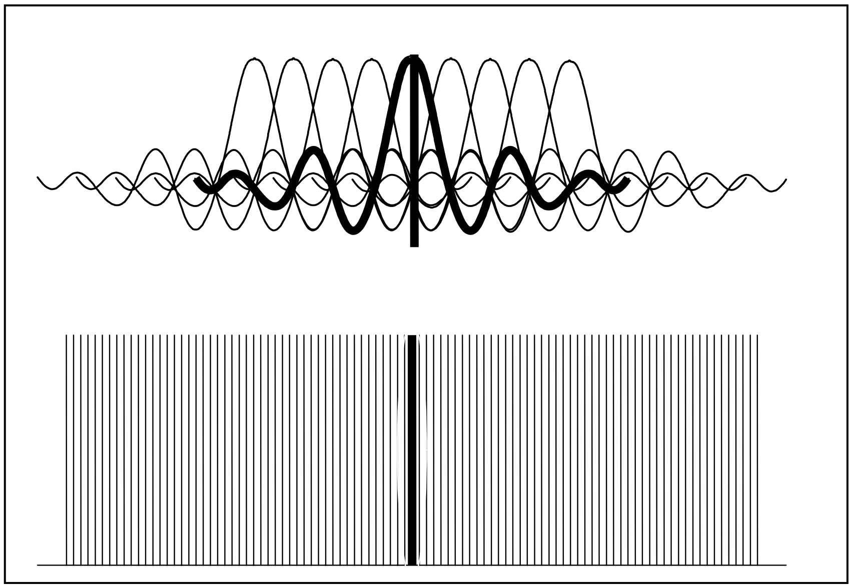

Fig. 4. The Relationship Between RF Carriers in COFDM

the modulation envelope appears to be 2000 distinct RF carriers, it is not generated by 2048 individual phase-locked voltage controlled oscillators. The COFDM carrier is mathematically derived in the transmitter by performing an Inverse Fast Fourier Transform (IFFT) on the waveform in the time domain to arrive at a representative waveform in the frequency domain. The resulting in-phase (I) and quadrature (Q) signals are then applied to the modulator and the RF waveform is amplified for transmission on the desired frequency band.

The spacing between carriers in a COFDM system is defined by the guard interval. Guard intervals are referred to as a fraction of the symbol time allocated to each carrier. Reflections or echoes that fall within the guard interval do not degrade the performance of the system. For a 2000 carrier QPSK system, a guard interval of 1/4 is equal to 56μs. When converted to distance this equates to approximately 48 kilometers. Therefore, a COFDM system operating in QPSK mode with a guard interval of 1/4 a multipath reflection at 0dB from as far away as 24 kilometers (one-half of the round trip distance) can be tolerated. A path loss calculation for 2200 MHz over a distance of 48 km indicates a path loss of -133 dB. Clearly, COFDM provides a high degree of rejection of unwanted reflections.

Each carrier is modulated using QPSK or 16-QAM at a low bit-rate. The aggregate bit-rate of the transmission is the sum of the number of carriers multiplied by the bit-rate of each individual carrier. For example, when transmitting a signal at 8 Mb/s the payload for each carrier is approximately 4 kb/s. In practice, a 2000 carrier system (2K) consists of 1705 payload carriers as some are designated for system overhead (synchronization and channel characterization, etc.). Additionally, the aggregate data throughput is dependent upon the channel coding (Viterbi and Reed-Solomon forward error correction) and guard interval selected. High code rates and short guard intervals (very high bandwidth applications) are more susceptible to interference issues than are low bandwidth applications (such as video at 8 Mp/s).

Code rates are expressed as fractions that define how much data bandwidth is available for user data transmission. Bandwidth not available for user data transmission is encumbered by forward error correction overhead. For example, a code rate of ¾ indicates that 75% of the total bandwidth is available for user data. Transmission data rates are affected by code rates and guard intervals for an 8 MHz COFDM system. By distributing the coded data across the available carriers in an interleaved, channel disturbances (selective fading) have even less impact on transmission system throughput.

Since the COFDM transmission system requires only 8 MHz of occupied spectrum, system gain is achieved by improving the carrier-to-noise ratio over that of an analog system occupying 16 MHz of spectrum. Additionally, more COFDM channels can be fit into any given amount of spectrum as compared to a conventional wideband analog video transmission system. Pacific Microwave Research has conducted testing that reveals a high tolerance for co-channel and adjacent channel interference with COFDM. In one instance, two systems were operated in close proximity on the same RF channel using different code rates and guard intervals with excellent results. For tactical operations, COFDM provides a high immunity to jamming.

Not all multipath related issues are a direct result of reflections in the environment. It is possible to encounter phase-delayed signals as a result of Doppler shift. Laboratory tests conducted in 1997 by Deutsche Telekom Berkom examined the effects of Doppler shift on a 2000 carrier COFDM system operating in QPSK and 16-QAM modes. The study used a channel simulator to quantify the increase in system carrier-to-noise (C/N) required to maintain image quality over a range of velocities. According to the results of the study, an increase of only 1.5 dB in C/N performance is required for both QPSK and 16-QAM operating at 1/2 code rate at a velocity of 50 km/h. Increasing the velocity from 50 km/h through 200 km/h in both cases did not require additional C/N improvement. The study indicated that in an urban environment (as would be found in MOUT operations), the predicted maximum vehicle speed for QPSK is 330 km/h and for 16-QAM is 240 km/h. In these modes, the payload capacity for QPSK is approximately 5 Mb/s and for 16-QAM is approximately 10 Mb/s. These data rates are more than adequate for high-quality imagery. In fact, multiple high-quality images could be transported at the 16-QAM data rate. Clearly, the performance degradation for COFDM systems as a function of Doppler shift at reasonable velocities is not a factor for effective tactical UAV operations.

A common criticism of COFDM systems is the apparent power inefficiency when compared to analog FM transmitters. While on the surface this appears to be the case, a complete system understanding helps put the issue in perspective. The primary reason COFDM transmitters produce less power output for a given primary power consumption is that the amplitude modulated carrier requires a high degree of linearity for proper operation. A typical linear amplifier for COFDM is operated 10 dB below the point an amplifier used for FM operation would be operated. For example, an amplifier that would deliver 5W of power in an analog FM application would be configured to provide 500 mW of power in a COFDM application. While less power is output from the amplifier in the COFDM application, the current consumption is the same as the FM application. This does not imply that a COFDM system provides 10 dB less performance than an FM system.

Bench characterization of COFDM systems by PMR has revealed that, under static conditions, the COFDM system will perform 10 dB better with respect to receiver threshold than an FM system.

Where an FM system fails at a level of -80 dBm, the COFDM system delivers excellent video down to -90 dBm. Additionally, the quality of the digital video image is consistent down to the minimum threshold while the analog video image becomes noisier as signal level is reduced. This is primarily due to the reduction in noise bandwidth of the receiver as the COFDM system occupies only 8 MHz of spectrum compared to a 16 MHz wide analog FM carrier.

However, while the playing field is leveled somewhat by virtue of the bandwidth improvement inherent in the COFDM system, performance in the field is substantially better with COFDM. This is a result of the frequency diversity afforded by the multi-carrier modulation system and the forward error correction applied to the data as described above. As a result, COFDM systems operating with an RF power level output 10 dB less than an analog FM video link will work substantially better in the real-world environment.

Pacific Microwave Research has conducted tests of its COFDM system in a variety of scenarios in both urban and rural environments using both directional and omni-directional antenna systems. When compared to analog FM systems, a COFDM transmission system behaves more as a "set it and forget it" appliance. As long as sufficient signal level is available, the system will deliver reliable video to the user. System performance is especially spectacular in an urban environment that is rife with short period multipath reflections. Such an environment would be consistent with MOUT operations where realtime aerial video imagery would provide valuable mission intelligence.

Another significant advantage for tactical operations using COFDM systems lies in the ability to scramble the bit-stream using an encryption key based algorithm to prevent unauthorized interception. Analog systems use cut and rotate scrambling technology that only provides a basic level of interception protection. With COFDM, it is possible to implement the 128-bit Advanced Encryption Scheme (AES) algorithm in the MPEG Transport Stream (MTS) to provide a high-degree of security. This digital encryption technology provides the type of security required when conducting surveillance on terrorism or national security targets. Use of the security feature in COFDM does not degrade system performance.

APPLICATIONS

PMR has developed a compact COFDM transmitter for tactical UAV applications following two years of development. Using a compact COFDM receiver, the system can deliver tactical UAV imagery to a mobile command post or even directly to dismounted troops to support realtime tactical deployment decisions and situational awareness. A variety of tactical video missions are possible when COFDM is used as the transmission mode. COFDM provides a non-line-of-sight video transmission system that can truly be used for mobile applications.

Assuming a tactical UAV configured with a visual or thermal sensor and a 2200 MHz COFDM transmission system outputting 1W into a 6 dB gain omni directional antenna (6 dB omni antenna at receive location) and operating at 1000 m, the expected operational range is approximately 25 km. This range is calculated with low-gain omni-directional antennas on each end of the link. This configuration is typical for tactical UAV support of MOUT operations. A compact directional antenna located at a temporary-fixed command post would provide even greater system range. It is important to recognize that within the 25 km mobile operational range, video link quality will be excellent as a result of the multipath rejection capabilities of COFDM.

In addition to tactical UAV applications, PMR envisages a compact and rugged digital video and audio transmitter worn by military team members with a helmet mounted or handheld video camera and noise canceling microphone. The helmet mounted camera (visual or thermal) captures images as the solider moves through the tactical area of interest. The soldier also provides voice narration of the scene over the digital audio channel. Command post and unit personnel receive and evaluate the images and sounds and then direct the soldier over a secure 2-way radio link to obtain additional imagery of special interest. Because of the benefits of a digital microwave link, the soldier can roam freely (without the requirement of maintaining line-of-sight) while providing reliable and secure imagery to the command post. Such a system would be useful in MOUT and Homeland Security applications for first responders.

The system provides substantial utility in MOUT operations because it is not necessary to maintain the line-of-sight conditions demanded of conventional analog FM video systems. Responders can move around corners and enter buildings while still providing command staff with high-quality video. All that is necessary with the COFDM system is sufficient energy reflected back through the environment to the command post receiver. Tactical observation systems using COFDM transmission technology can be quickly attached to buildings or other structures, or even air-dropped, to provide command structure and troops with real-time video surveillance of key objectives. This video intelligence will provide a significant operational advantage and ultimately save lives in military and first responder missions.

SUMMARY

Digital video transmission using Coded Orthogonal Frequency Division Multiplex is a transmission technique that will transform the quality and reliability of video collection activities for military operations. The technology's ability to perform exceptionally well in a multipath environment with simple omni-directional antennas makes it ideal for tactical operations in both the battlefield and urban environments. Tactical UAV's using COFDM can provide reliable and secure close-in aerial intelligence direct to field command units and dismounted troops. Advanced scrambling of the COFDM signal in the digital domain reduces the risk of unintentional interception. COFDM is well suited for tactical UAV and MOUT missions where simple and lightweight portable equipment is required for mobile operations. COFDM provides reliable and secure non-line-of-sight digital video transmission to a variety of military missions.