Image transmission through sensor systems: theoretical and experimental results

David C. Hartup, Brian A. Marks, Thomas A. Fishburn
Nova Engineering, 5 Circle Freeway Dr., Cincinnati, OH 45246

ABSTRACT

Historically, tactical sensor systems have transmitted limited amounts of data. Alert notifications, control signals, and status can be quickly transmitted using low rate data links such as 1200 bps. Increasingly, there is a desire to transmit more data through sensor systems. Signals may consist of E/O or IR images, acoustic or seismic signals, or near real-time target location information. Such capabilities are desired for Future Combat Systems, Objective Force Warrior, and the Objective Force. This paper addresses the ability of existing sensor systems to reliably provide timely transmission of large data files. Specifically, transmission of image files through sensor systems is analyzed. A theoretical analysis gives the probability of error-free image transmission, practical transmission distances, and the transmission time required. Experimental results that validate assumptions made in the theoretical analysis are given. Experimental results show that some existing sensor systems are fully capable of providing low latency, reliable image transmission.

Keywords: Sensor systems, image transmission, tactical communications

1. INTRODUCTION

Fielded, tactical sensor systems are typically used in a manner that does not generate large amounts of data or require high data rate transmission. Signals transmitted from a control center to a remote sensor typically consist of control and configuration commands. These signals can be quickly transmitted using low rate data links such as 1200 or 9600 bps. In the reverse data link direction, information transmitted from a remote sensor to a control center typically consists of alert notifications, command acknowledgements, sensor coordinates, or status messages. Again, latency requirements can easily be met using low rate data links.

In modern deployments there is a strong desire for transmission of larger data files. For example, transmission of EO or IR images may be desired to enable positive identification of a target. Additionally, many recent sensor system deployments use multiple sensors in a small area so that accurate location information can be obtained by combining the information recorded by each sensor. In these sensor arrays, combined processing of acoustic, seismic, or ground-based radar signals from multiple sensor locations requires information from each sensor to be transferred to a single processing node[1]. In other applications, fusion of different types of information from various sensors again requires data from multiple sensors to be transmitted to a common processing node[2]. Due to latency concerns, transmission of these larger data files requires a higher data rate than is used in some legacy sensor systems.

Some manufacturers have anticipated the need for higher data rate transmission through sensor systems. Hardware has been developed that utilizes spectrally efficient waveforms operating at higher data rates than previous sensor systems[3]. This paper quantifies the performance of these systems with regard to meeting the needs of low latency, large file transmission required by current tactical sensor system deployments. Because the use of repeaters increases the latency and potentially affects the message error rate, this paper addresses overall system performance including repeaters.

Section 2 of this paper describes the system transmission parameters and underlying assumptions that are used in the analysis. Section 3 presents a theoretical analysis that results in message error rates, the number of repeaters needed in a specified deployment, and required message transmission time. Section 4 covers experimental results that were obtained to validate the assumptions in Section 2, and to verify the theoretical analysis of Section 3. Section 5 provides conclusions.

2. SYSTEM CONFIGURATION AND TRANSMISSION PARAMETERS

Figure 1 shows a sensor system deployment that could be used for IR or EO monitoring of a remote site. At the sensor deployment location, an imaging controller, shown as a Remote Intelligent Communications Controller (RICC) in Figure 1, is used to coordinate the functions of a cueing sensor (not shown) and an imaging sensor. The cueing sensor, which might be seismic, acoustic, or IR, activates the main imaging sensor when a potential target is present. Using a cueing sensor extends system lifetime by conserving energy consumption of the imaging device. The RICC also serves as a transmitter and receiver. As shown in Figure 1, the image data from the RICC is transferred to a distant Hand-Held Programmer-Monitor (HHPM) using Radio Repeaters (RRs). The distance between the imaging device and the HHPM is assumed to be 45 km for the following analysis.

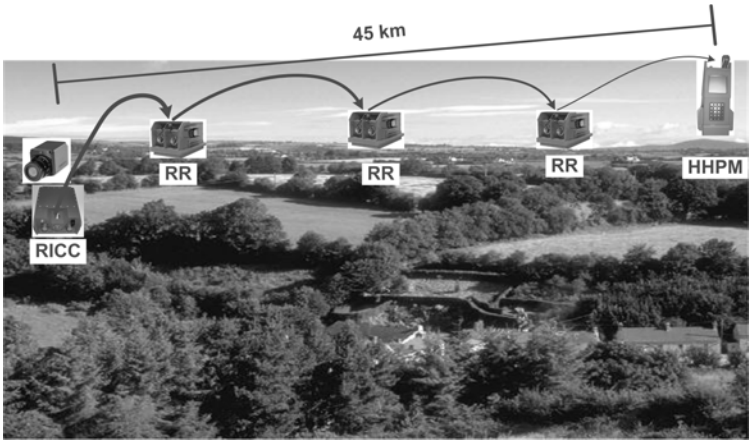


Figure 1: Typical sensor system deployment, RICC=Remote Intelligent Communications Controller, RR=Radio Repeater, HHPM=Hand-Held Programmer-Monitor

System performance is analyzed using two types of RRs, the Army REMBASS RT-1175C and the Marines TRSS RT-1847, both developed and produced by Nova Engineering. The two (physically similar) devices appear in Figure 2 (note the deeper bottom cover on the RT-1847).

Figure 2: Nova Engineering's REMBASS II RT-1175C Radio Repeater and TRSS RT-1847 Radio-Repeater

The RT-1175C allows an operator to configure its radio channels and device IDs using a PSQ-7, PSQ-16, or laptop running HyperTerminal. Once configured and implanted, the RT-1175C retransmits received VHF 1200 bps messages over an inbound (sensor-to-command center) path. The RT also retransmits VHF 9600 bps messages bi-directionally over separate inbound and outbound communication paths. The RT-1175C satisfies requirements for an elementary repeater and, as such, does not process messages addressed to it and cannot be reconfigured or controlled remotely over the air.

The RT-1847 can also be configured using a laptop and retransmits VHF 1200 and 9600 bps messages in a fashion identical to that of the RT-1175C. Unlike the RT-1175C, the RT-1847 processes command messages addressed to it and can be reconfigured and controlled remotely, even after implant. As shown in Figure 1, the RT-1847 has an additional chamber mounted below the bottom panel level of the RT-1175C. This chamber houses a UHF transceiver that can be used to convey large blocks of data at higher data rates of 32 and 56 kbps.

Table 1 shows the repeater and system parameters that are used for this analysis.

Parameter	RT-1175C / RT-1847	RT-1847
Operating Frequency Range	VHF	UHF
Data Rates (bits/sec)	9600	32000, 56000
Sensitivity (dBm)	-107	-105 for 32000 -103 for 56000
BER at Sensitivity	1e-4	1e-4
Output Power (dBm)	33 min	37 min
Antenna Gain	0 dBi	2 dBi

Table 1: Parameters used in analysis

The sensitivities and output powers listed in Table 1 are worst case specifications. Measurement of antenna gain is subject to many variables. Values of 0 dBi for VHF and 2 dBi for UHF are used based on measurements and information from the manufacturer. As shown in Section 4, results from measured system performance correlate with the value assumed here. The RICC transmit and HHPM receive parameters are the same as those shown in Table 1.

As can be seen from Figure 1, propagation is along the ground. Sensor systems typically use Line-of-Sight (LOS) antenna positioning, and this will be assumed here. Propagation loss along the ground is dependent on many variables, difficult to predict, and attenuation values can vary significantly in seemingly similar deployment conditions. The Bullington model[4] predicts a $1/R^4$ loss characteristic, where R is the propagation distance. This model is designed for cases where both transmit and receive antennas are located very close to the ground. In a typical deployment, antennas for repeaters can be elevated, either by using a mast, convenient existing structure, or mounting in a tree. For these situations, a loss characteristic of $1/R^3$ has been found to more closely match experimental data. With the exception of the first link from the RICC located at the sensor site, the $1/R^3$ characteristic is used in the analysis of Section 3. The data link from the RICC to the first repeater is treated differently because the antenna on the RICC is typically located close to the ground to maintain system covertness. For this link, the transmission distance is assumed to be half of that predicted using a $1/R^3$ propagation loss characteristic.

Image file size is a key parameter in the analysis. The size of an image file is dependent on required image resolution, which is dependent on the application. File size is also dependent on the compression technique used. Experience has shown that an 8-bit grayscale image of 352 by 240 pixels, compressed using JPEG 2000 to a level such that near original quality is maintained, will result in a file size of 3 to 4 kbytes. For the following analysis, an image size of 5 kbytes is assumed.

3. THEORETICAL RESULTS

This section uses the assumptions stated in Section 2 to evaluate the probability of error and the latency that result when transmitting a 5 kbyte message over 45 km, as shown in Figure 1. Results are obtained for VHF and UHF operation. The analysis will be described in detail for the VHF link. Results presented for the UHF link were obtained by repeating the analysis with parameters appropriate for UHF operation.

The first step in the analysis is to determine the number of repeaters that are required to close the communication link. For a $1/R^3$ characteristic, the propagation loss in dB is

$$L_{path}\,(\mathrm{dB}) = 20\cdot\log[c/(4\pi\cdot f\cdot R^{1.5})]$$

where L_{path} is the path loss in dB and c is the speed of propagation. The maximum path loss at which the link can be closed, $L_{path,\ max}$ can be used to express the equality

$$P_T - P_{sen} + G_{TX} + G_{RX} + L_{path,max} = 0$$

where P_T is the transmit power in dBm, P_{sen} is the receiver sensitivity in dBm, G_{TX} is the transmit antenna gain in dBi, G_{RX} is the receive antenna gain in dBi, and $L_{path,\ max}$ is the maximum path loss in dB at which the link can be closed. The maximum transmit range, R_{max}, can be calculated using the equation above and is

$$R_{max} = 10^{(P_T - P_{sen} + G_{TX} + G_{RX} + 20\log(c/(4\pi \cdot f)))/30}$$

Using the parameters given in Section 2 for the VHF link and a frequency of 160 MHz, R_{max} is found to be 13 km. Letting the link distance between the RICC and the first RR be half of the distance between successive RRs, the number of repeaters, $N_{repeaters}$, required to cover at least 45 km is 3. The actual distance that could be covered is 45.5 km. For the following analysis, it should be noted that the number of transmissions required to send a message from the RICC to the HHPM is $N_{repeaters} + 1$.

The probability of a message error is dependent on the data structure and forward error correction. A typical data transmission system groups several bits into a block, and several blocks are assembled into a larger data structure called a packet. One variation of block code error correction, the BCH (63,51) code, can correct 2 bit errors in each 63 bit block. Therefore, using a worst case bit error rate (BER), P_b, of 10e-4, the probability of receiving a block with no errors, $P_{Block,\ error\text{-}free}$, is

$$\begin{aligned} P_{Block,\ error\text{-}free} &= (1-P_b)^{63} + 63 \cdot (1-P_b)^{62} \cdot P_b + (63!/(61! \cdot 2!))(1-P_b)^{61} \cdot P_b^{\,2} \\ &= 0.999999960467280 \end{aligned}$$

The 63 bit data blocks can be arranged in packet sizes of 256 bytes. This results in the number of blocks per packet as

$$\begin{aligned} N_{blocks\ per\ packet} &= 256*8/63 \\ &= 32 \end{aligned}$$

where the above result is rounded down to the nearest integer to prevent transmission of a partial packet.

Now the number of packets required to transmit a 5 kbyte file is determined. Error correction adds 12 bits to every 63 bit packet. This leaves 51 bits for image data and overhead data. Often, packets have an overhead of about 10% of the data length, or in this case, about 5 bits for each set of 51 bits not used for error correction. This leaves 46 bits of each 63 bit block for data transmission. Equivalently, 46·32, or 1472 bits of image data can be transmitted per packet. Therefore, the number of packets required to transmit a 5 kbyte file is

$$\begin{aligned} N_{packets\ for\ 5\ kbyte\ file} &= 5 \cdot 1024 \cdot 8/1472 \\ &= 28 \end{aligned}$$

where the above result is rounded up to the nearest integer to insure all of the image bits are transmitted. Using the above results and the fact that repeaters correct errors in each block before retransmission, the probability of transmitting a 5 kbyte file over 45 km with no errors is

$$\begin{aligned} P_{no\ errors,\ 5kbyte,\ 45\ km} &= (P_{Block,\ error\text{-}free})^{N_{blocks\ per\ packet} \cdot N_{packets\ for\ 5\ kbyte\ file} \cdot (N_{repeaters}+1)} \\ &= 0.999999960467280^{(32 \cdot 28 \cdot (3+1))} \\ &= 0.999858325 \end{aligned}$$

The result shows that less than 1 in 7,000 files will have one or more packet errors. Experimental evidence has shown that files containing only 1 packet error often have only minor distortions in the image. An analysis similar to that above shows that less than 1 file in 100,000,000 will have 2 or more packet errors.

Now the latency in sending the file is analyzed. Because the data rate is 9600 bps, the time required to send one data packet of 256 bytes is

$$\begin{aligned} T_{\text{packet}} &= (256*8)/9600 \\ &= 0.213 \text{ sec} \end{aligned}$$

Each transceiver shown in Figure 1 operates by receiving a data packet and then transmitting the packet to the next receiver before receiving the following packet. Therefore, to achieve maximum efficiency, transmission of a message proceeds as shown in Figure 3.

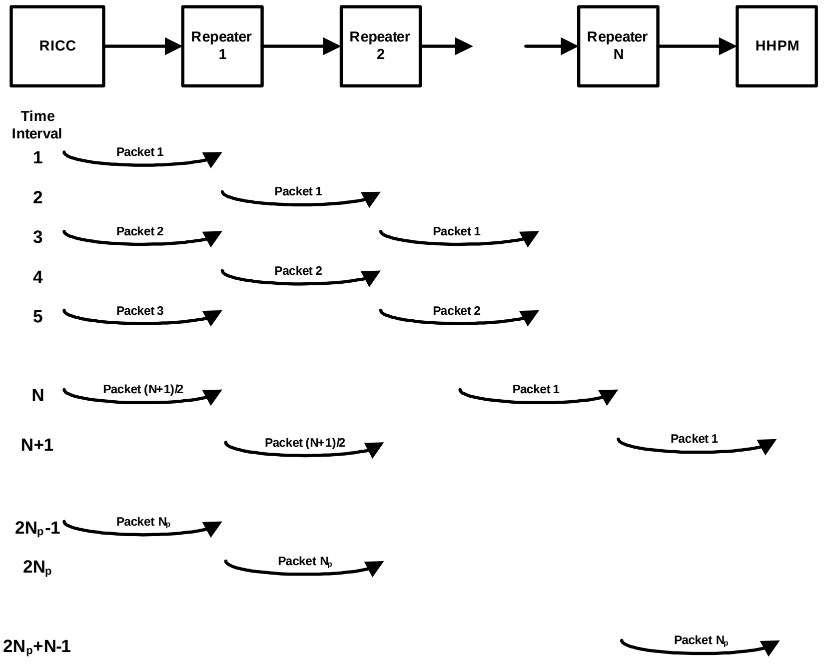


Figure 3: Packet transmission protocol, N_p = number of packets to be transmitted, N = number of repeaters

The time required to transmit a 5 kbyte file is

$$\begin{aligned} T_{5\text{ kbyte}} &= (2 \cdot N_{\text{packets for 5 kbyte file}} + N_{\text{repeaters}} - 1) \cdot T_{\text{packet}} \\ &= 12.4 \text{ sec} \end{aligned}$$

However, in addition to the delays shown above, the RRs have a small delay between the end of reception and start of retransmission. This brings the total transmission time to approximately 15 seconds.

The analysis above was repeated for the UHF mode of the RT-1847. For this case, results were determined for data rates of 32 and 56 kbps. The transmission frequency used for the analysis was 300 MHz.

The results for the UHF mode, along with results from above for the VHF mode are summarized in Table 2. It can be seen that the probability of image transmission with no errors is very high in all three cases. The main difference is that the latency is significantly reduced for data rates of 32 and 56 kbps.

Performance/Requirement	Result Using RT-1175C / RT-1847 VHF Parameters (9600 bps)	Result Using RT-1847 UHF Parameters (32 kbps)	Result Using RT-1847 UHF Parameters (56 kbps)

Performance/Requirement	Result Using RT-1175C / RT-1847 VHF Parameters (9600 bps)	Result Using RT-1847 UHF Parameters (32 kbps)	Result Using RT-1847 UHF Parameters (56 kbps)
Total transmit distance	45 km	45 km	45 km
Number of repeaters required	3	3	4
Maximum distance between repeaters	13.1 km	13.6 km	11.7 km
Maximum distance covered	45.7 km	47.6 km	52.5 km
Probability of image transmission with no errors	99.986%	99.986%	99.982%
Time to transmit a 5 kbyte image	15 sec	4.5 sec	2.6 sec

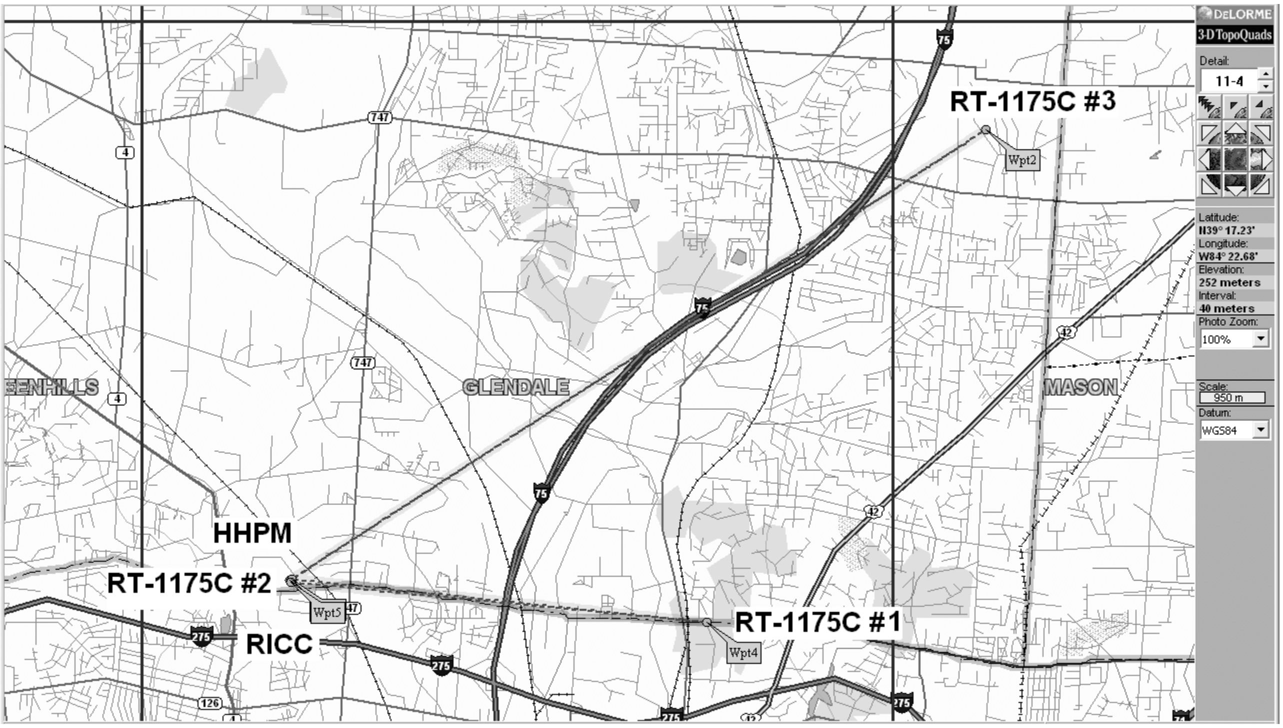
Table 2: Number of repeaters required, probability of image transmission with no errors, and latency for transmission of a 5 kbyte file across 45 km using the RT-1175C and RT-1847 Radio Repeaters

4. EXPERIMENTAL RESULTS

The objective of the experimental work was to demonstrate transmission of an image using several RT-1175C Radio Repeaters, and to verify the assumptions made in Section 2. A RICC was used to capture an image; divide the image into message packets; and transmit the packets over the VHF link at 9600 bps. The packets were transmitted through three RT-1175C repeaters to an HHPM serving as the monitoring device.

The experiment was performed near Nova Engineering's facility, located north of Cincinnati, Ohio. The locations of the RICC, RRs, and HHPM are indicated on the map in Figure 4. The RICC was positioned outside the headquarters of Nova Engineering at ground level and the unit was outfitted with a 12 inch dual-band VHF/UHF stub antenna. The first link covered 6 km to RT-1175C #1 located in a public park to the east of Nova's building. The antenna for repeater #1, a 24 inch whip with four 15 inch ground radials, was remotely mounted in a tree approximately 6 m above the ground. To minimize the number of remote stations needed, the second link returned on the same 6 km path to RT-1175C #2 located at Nova Engineering. The antenna for repeater #2 was remotely mounted in a tree approximately 3 m above the ground. The third link covered 12 km to RT-1175C #3 located at the Voice of America facility to the northeast of Nova. The antenna for repeater #3 was remotely mounted in a tree approximately 3 m above the ground. The fourth link returned along the same 12 km path from repeater #3 to the HHPM located at Nova Engineering. The HHPM was connected to an antenna located on the roof of the building, approximately 10 m above the ground.

Noting the data transmission procedure shown in Figure 3, with the HHPM, RICC, and the second repeater all located at Nova Engineering, interference would be experienced if each transmission took place on a common frequency. Therefore, to avoid interference, each device in the transmission chain was assigned to one of 5 frequencies from a group of adjacent channels.



Detail: 11-4
Latitude: N39° 17.23'
Longitude: W84° 22.68'
Elevation: 252 meters
Interval: 40 meters
Photo Zoom: 100%
Scale: 950 m
Datum: WGS84

Figure 4: Transmission locations for the experimental field test

The profile of the terrain covered by this route is shown in Figure 5. The experiment covered a total link distance of 36 km. Due to the desire to minimize the number of remote stations, and therefore positioning of repeater #2 at Nova Engineering with the RICC and the HHPM, link 2 was limited to the 6 km distance covered by link 1. While link 1 was limited in distance by positioning of the RICC antenna near the ground, link 2 could have covered a much greater distance due to slightly elevated antenna placement. Link 2 is capable of covering the same 12 km distance as link 3 between repeaters #2 and #3. In fact, both link 3 from repeater #2 to repeater #3 and link 4 from repeater #3 to the HHPM were tested and found to have over 6 dB of margin. Closing a 12 km link with 6 dB of margin means that a distance up to 19 km could be covered, which would have resulted in a total system distance of 66.5 km, well beyond the requirement of 45 km used in the theoretical analysis. A summary of the test parameters and results is shown in Table 3.

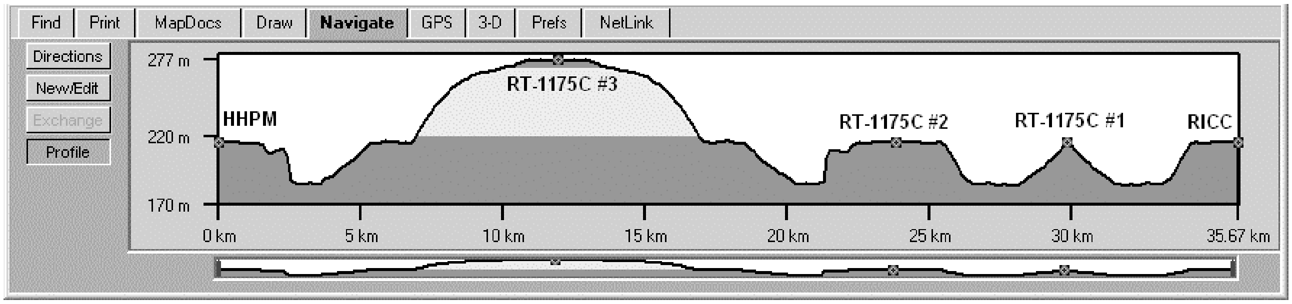


Figure 5: Field testing terrain profile

		Link 1		**Link 2**		**Link 3**		**Link 4**	
	Location 1 Nova Engineering		**Location 2 Public Park**		**Location 3 Nova Engineering**		**Location 4 Voice of America**		**Location 5 Nova Engineering**
Hardware	RICC		RT-1175C		RT-1175C		RT-1175C		HHPM
Elevation	215 m		215 m		215 m		276 m		215 m
Antenna	12" stub		24" whip with four 15" ground radials		24" whip with four 15" ground radials		24" whip with four 15" ground radials		24" whip with four 15" ground radials
Antenna Height	0.4 m (ground level)		6 m (in tree)		3 m (in tree)		3 m (in tree)		10 m (on roof)
Distance		6 km		6 km		12 km		12 km	
Margin		Not Tested		Not Tested		6 dB		6 dB	

Table 3: Field testing parameters and results

After completion of individual link testing, images were transmitted through the system. An example of a tested image is shown in Figure 6. While precision latency measurements were not taken, experimentally it was found that the latency was close to the 15 seconds that was obtained theoretically for the 9600 bps data rate.

Figure 6: Transmitted test image

5. CONCLUSIONS

Although existing sensor system hardware is often designed for transfer of information at low data rates, it has been shown that the RT-1175C and RT-1847 Radio Repeaters satisfy the need for low latency, robust transmission of images. A 5 kbyte image file can be transmitted across 45 km using 3 RT-1175C Radio Repeaters. The image will be received with zero packet errors more than 99.986% of the time and latency will be approximately 15 seconds. To reduce the latency, the 32 and 56 kbps modes of the RT-1847 Radio Repeater can be used. In this case, closing the link requires 3 repeaters at 32 kbps and 4 repeaters at 56 kbps. The images will be received error-free greater than 99.982% of the time. The latency will be approximately 4.5 seconds for the 32 kbps mode and 2.6 seconds for the 56 kbps mode.

REFERENCES

1. R. Moses, D. Krishnamurthy, and R. Patterson, A Self-Localization Method for Wireless Sensor Networks, Eurasip Journal on Applied Signal Processing, Special Issue on Sensor Networks, Vol. 2003, No. 4, Mar. 2003, pp. 148-158.

2. W. Yuan, S. V. Krishnamurthy, and S. K. Tripathi, Synchronization of Multiple Levels of Data Fusion in Wireless Sensor Networks, IEEE Global Communications Conference (GLOBECOM'03), Vol. 22, No. 1, Dec. 2003, pp. 221-225.

3. T. J. Bruns, R. J. O'Connell, J. S. Wells, and M. Dapper, Unattended Ground Sensor (UGS) Systems for Homeland Defense, Proceedings of SPIE -- Volume 5071, Sensors, and Command, Control, Communications, and Intelligence (C3I) Technologies for Homeland Defense and Law Enforcement II, Edward M. Carapezza, Editor, September 2003, pp. 280-288.

4. K. Bullington, Radio Propagation Fundamentals, *Bell System Tech. J.*, Vol. 36, May 1957, pp. 593-626.