A glimpse into a typical factory reveals a high degree of automation has entered into the work place. Computer-driven automated test benches, wire-guided robots and FC-controlled drill presses are a few examples of the proliferation of computer technology and automation in manufacturing. The boom in automation has created a need for reliable real-time communications in factories. In 1985, the Manufacturing Automation Protocol (MAP) networking standard was established by manufacturing leaders to encourage commercialization of high data rate communications hardware for use in computer-controlled manufacturing. MAP is capable of supporting 10 megabit per second (Mbps) data rates for short periods. MAP networks (and TOP networks in office buildings) rely on coaxial cable or fiber optic cable to interconnect users. Twisted-pair interconnection of computer terminals is also commonly used. This article discusses the use of radio links for communication in modern factories.

The method for transporting parts-in-process in a futuristic, but realistic, just-in-time (JIT) manufacturing environment is one of the areas of research at the National Science Foundation (NSF) Engineering Research Center (ERC) for Intelligent Manufacturing Systems. Analysis has shown that an inexpensive, agile mobile robot fleet, capable of navigating without any type of pre-made track, could easily accommodate the type of material flow required for a JIT manufacturing system. A truly autonomous guided vehicle (AGV) that does not use any type of tether will require a radio system for control. Optical systems are viable, but become inoperative when obstructed. Furthermore, radio systems will be useful for quickly and cheaply connecting often moved manufacturing equipment and computer terminals. Radio will also accommodate reconfigurable voice/data communications for other facets of factory and office building operation and may eventually be used in homes and offices to provide universal digital portable communications (1).

Presently, communications between computers and automated machines are conducted almost exclusively over cables. Narrowband radio systems (with data rates less than 10 kbps) are currently used in some factories for dedicated control of overhead cranes and wire-guided vehicles and for inventory control. While narrowband systems are well-suited for human operation and simple communications, it is anticipated that for a moderately sized AGV fleet (greater than 25 vehicles), data rates of several hundred kbps will be needed to accommodate real-time computer control and navigation of CIM-Integrated AGV systems employing multiple-access radio networking.

In the United States, the FCC has allocated spectrum for narrowband industrial radio communications in VHF (450 MHz) and UHF (900 MHz) bands. More recently, the FCC has authorized the use of suitably designed spread-spectrum systems for 900 MHz, 2400 MHz and 5725 MHz (3). If transmitters meet with FCC approval, unlicensed 1 W transmitter power levels may be used over bandwidths greater than 25 MHz. In Japan, spectrum has been set aside for 300 mW, 4800 bps indoor radio systems operating in the 400 MHz and 2450 MHz bands (4).

Accurate characterization of the operating channel is a mandatory prerequisite for the development of reliable wideband indoor radio systems. Radio channel propagation data from factory buildings have been made available for the first time through a research program sponsored by NSF and Purdue University. As shown here, it is not environmental noise, but rather multipath propagation that limits the capacity of a radio link. The severity of multipath is largely dependent upon factory inventory, and building structure and age.

Factory Noise

Although much of the radio noise encountered in factories arises from weak emitting sources, measurements have revealed that some types of industrial equipment emit harmonic RF energy and can radiate substantial noise up to several hundred megahertz (8). Equipment such as RF-stabilized arc welders, induction heaters and plastic bonder are acute sources of noise. Although interference is significant at HF and VHF, noise signatures of such equipment fall off rapidly above 1 GHz (3). Recent empirical measurements have confirmed that typical machine-generated noise levels in operational factories are much less severe at higher frequencies (9). Figure 1 shows results of peak noise power spectrum measurements made along an engine manufacturing transfer line in full operation. Worst-case noise levels are seen to be...
40 dB lower at UHF/microwave frequencies and are only 5 dB above the thermal noise floor. These results are encouraging and indicate that noise will not severely hamper most factory radio systems operating at UHF and above.

**Multiple-Access Networking Considerations**

Future factory radio communication systems will rely on multiple-access techniques to accommodate many fixed and portable/mobile terminals. Multiple-access techniques such as frequency division multiple-access (FDMA), time-division multiple access (TDMA), code division multiple-access (CDMA, also called spread-spectrum) and carrier-sense multiple-access (CSMA, also called packet carrying medium access) channel users into non-overlapping signal spaces. Because of non-ideal conditions, however, there is inevitable overlapping of signals and the resulting co-channel interference can appear as lengthy message delays or as degradation of the desired received signal.

Random access (CSMA, CDMA) radio local area networks are attractive because they have relatively few synchronization requirements. Unlike fixed assignment networks (FDMA, TDMA) which assume all users require their own channel, random access techniques rely on "bursty users" and assume that the likelihood of many users using the network at one time is small. For AGVs using reliable on-board dead-reckoning systems, infrequent position updates...
suggest the use of random access networks for AGV control. On the other hand, direct remote control of a fleet of vehicles by a central dispatching station (such as might be warranted for cleaning a contaminated nuclear reactor) would warrant a fixed assignment scheme.

At the ERC for Intelligent Manufacturing Systems at Purdue University, considerable progress has been made in determining realistic limitations on the delay characteristics of packet radio networks (10). Also, a powerful product form solution model for packet radio systems has been developed (11). CSMA and CDMA strategies can be merged to enhance multiple-access communication performance in a multipath environment while providing some ranging capability (12,13). In Reference 12, fundamental expressions that permit the calculation of bit error rates in packet spread-spectrum systems have been provided; these expressions permit system designers to analyze throughput and delay as functions of the number of simultaneous users.

As the number of users increases, the real-time communications capability of random access techniques diminishes, and a fixed assignment approach is required. Furthermore, if central computers using parallel processing architectures are required to simultaneously communicate, navigate and control many simultaneous users on a virtually continuous basis, TDMA or FDMA approaches will be desired. Portable/mobile users transmitting large blocks of data (i.e., MIS, video transmissions, high resolution graphics, maps) are accommodated best by a fixed assignment network. Selection of networking strategies of radio depends heavily upon the number of users, the duration of transmissions, the limit of sophistication at each terminal, and the importance of real-time control.

**Multipath Propagation**

Due to the large metal content of a factory, multipath interference is created by multiple reflections of the transmitted signal from the building structure and surrounding inventory. The resultant received waveform is a sum of time and frequency-shifted versions of the original transmission and, depending on parameters of the signal and channel, the received signal may be greatly distorted.

Historically, multipath has been identified as the most limiting factor in portable radio communication systems. For narrowband factory radio systems, multipath causes large fluctuations (fading) in received signal levels due to temporal variations of the channel and the receiver. Additional signal loss will occur when an AGV is shadowed by inventory and equipment. In wideband systems, the scatterers create intersymbol interference and cause the channel to be frequency selective. Consequently, the maximum data rate supported by a multipath channel is limited. Typical fading channels require 30 dB more transmitter power to achieve low bit-error rates ($10^{-4}$) compared to non-fading systems.
rf indoor communications

Table 1. Path loss exponent as a function of factory site.

<table>
<thead>
<tr>
<th>Factory Site</th>
<th>n</th>
<th>α (dB)</th>
<th>No. of Points</th>
<th>Corr. Coef.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site B</td>
<td>2.39</td>
<td>10.20</td>
<td>33</td>
<td>.94</td>
</tr>
<tr>
<td>Site C</td>
<td>1.89</td>
<td>5.55</td>
<td>41</td>
<td>.98</td>
</tr>
<tr>
<td>Site D</td>
<td>2.43</td>
<td>7.94</td>
<td>34</td>
<td>.96</td>
</tr>
<tr>
<td>Site E</td>
<td>2.12</td>
<td>8.03</td>
<td>18</td>
<td>.96</td>
</tr>
<tr>
<td>Site F</td>
<td>1.92</td>
<td>4.79</td>
<td>17</td>
<td>.98</td>
</tr>
</tbody>
</table>

Table 2. Path loss exponent as function of factory topography.

<table>
<thead>
<tr>
<th>Factory Geography</th>
<th>n</th>
<th>α (dB)</th>
<th>No. of Points</th>
<th>Corr. Coef.</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOS light clutter</td>
<td>1.79</td>
<td>4.55</td>
<td>26</td>
<td>.98</td>
</tr>
<tr>
<td>LOS heavy clutter</td>
<td>1.79</td>
<td>4.42</td>
<td>43</td>
<td>.98</td>
</tr>
<tr>
<td>LOS along wall</td>
<td>1.49</td>
<td>3.9</td>
<td>6</td>
<td>.99</td>
</tr>
<tr>
<td>OBS light clutter</td>
<td>2.38</td>
<td>4.67</td>
<td>23</td>
<td>.99</td>
</tr>
<tr>
<td>OBS heavy clutter</td>
<td>2.81</td>
<td>8.09</td>
<td>43</td>
<td>.97</td>
</tr>
<tr>
<td>All Geographies*</td>
<td>2.18</td>
<td>7.92</td>
<td>135</td>
<td>.96</td>
</tr>
</tbody>
</table>

*LOS measurements along wall not included in computation.

Table 3. Shadowing effects of some common factory equipment.

<table>
<thead>
<tr>
<th>Obstacle Description</th>
<th>Attenuation (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5 m storage rack with small metal parts (loosely packed)</td>
<td>4-6</td>
</tr>
<tr>
<td>4 m metal box storage</td>
<td>10-12</td>
</tr>
<tr>
<td>5 m storage rack with paper products (loosely packed)</td>
<td>2-4</td>
</tr>
<tr>
<td>5 m storage rack with paper products (tightly packed)</td>
<td>6</td>
</tr>
<tr>
<td>5 m storage rack with large metal parts (tightly packed)</td>
<td>20</td>
</tr>
<tr>
<td>Typical N/C machine</td>
<td>8-10</td>
</tr>
<tr>
<td>Semi-automated Assembly Line</td>
<td>5-7</td>
</tr>
<tr>
<td>0.6 m square reinforced concrete pillar</td>
<td>12-14</td>
</tr>
<tr>
<td>Stainless Steel Piping for Cook-Cool Process</td>
<td>15</td>
</tr>
<tr>
<td>Concrete wall</td>
<td>8-15</td>
</tr>
<tr>
<td>Concrete floor</td>
<td>10</td>
</tr>
</tbody>
</table>

To determine propagation characteristics inside factory buildings, radio wave propagation experiments at 1300 MHz were made in five fully operational factories (14). Over 30,000 narrowband fading measurements and 950 wideband impulse response measurements were made in a diverse collection of industries and building structures. Factories that participated in the research included leading engine and automobile parts manufacturers and dry-foods producers. An overview of the experiments and the measurement equipment are given in (15). Briefly, four distinct topographical settings were identified in each of the five factories. Topographies ranged from line-of-sight (LOS) transmission paths along lightly cluttered aisles to fluffly cluttered, obstructed paths between adjacent aisles. In each topography, three measurement locations were selected, with graduated transmitter-receiver separations between 20 and 80 m. The transmitter was positioned in the clear in the center of the particular topography while the receiver was moved along 1 m tracks at each measurement location.

Wideband channel impulse responses were measured in the time domain by repeatedly transmitting a 10 ns pulse and receiving on a digital storage oscilloscope the attenuated, distorted and delayed versions of the pulse. The measurement apparatus consisted of a periodic pulse-modulated transmitter with a peak output power of 1 W. The receiver consisted of a low noise amplifier followed by a square law envelope detector and a 350 MHz digital storage oscilloscope. A directional coupler allowed CW envelope measurements to be made simultaneously by a modified communications receiver. The measurement system block diagram is shown in Figure 2. Wideband discone antennas (16) were used at both transmitter and receiver.

CW measurements revealed that path loss falls off exponentially with distance and is described by a log-normal distribution about a mean path loss law given by:

Path loss(d) = 10αd

where d is the distance between transmitter and receiver in meters and n is the mean path loss exponent found by using a linear least squares fit to a scatter plot of measured path loss against measured distance (17). This model has also been found to hold at UHF for channels inside and around houses (2). Figure 3 shows the received signal strengths relative to a reference measurement (made at 10 wavelength distance) over various topographies at all five factories. Tables 1 and 2 indicate that in all cases, received power and T-R separation are highly correlated, thus confirming that equation 1 is a valid model for factory radio systems. Furthermore, although signals attenuate more rapidly with distance in obstructed topographies, the worst case attenuation is not as severe as in partitioned homes and office buildings (18,19). This is due to large ceiling expanses, wide aisles, and metal ceiling truss work and inventory that readily facilitate multiple paths.

Because accurate descriptions of path obstacles were kept during the factory measurements, it is possible to extract from the data the RF signal loss caused by typical factory surroundings. By comparing the received signal levels for shadowed locations with the ensemble average of the factory measurements, shadowing losses have been computed. Table 3 indicates typical shadowing losses that can occur when a receiver is placed directly behind an obstruction (deep shadowing). The data reveal that knife-edge diffraction theory is pessimistic; deeply shadowed locations experience received signal levels consistently

January 1989
5 to 20 dB larger than predicted by knife-edge diffraction. For long paths with obstructions located in the middle of the path, knife-edge diffraction is in better agreement with the empirical data.

Measurements made with a moving CW receiver over many local areas reveal that fading is usually Rayleigh in heavily cluttered LOS and lightly cluttered Rician for paths along perimeter walls and over lightly cluttered LOS paths, and log-normal for paths that traverse heavily cluttered obstructed topographies. Figure 4 illustrates some of these typical fading distributions and their fit to some of the observed fading data.

Additional CW measurements were made to determine the temporal variation of factory channels caused by motion of personnel and work in progress. The transmitter and receiver were positioned to traverse busy assembly lines and main aisles. Figure 5 shows a typical measurement and the corresponding changes in signal strength over several seconds. Figure 6 illustrates that temporal fading between fixed radio terminals is well described by a Rician distribution having K 10 dB.

Measurements made over identical paths with different receiver antenna heights reveal that received signal strengths are often highly correlated (not independent) for separations of 2 wavelengths (0.5 m). As seen in Figure 7, however, close-spaced antenna diversity may be useful when antennas are located in a horizontal plane in line with the LOS path. Energy density antennas that couple both electric and magnetic fields may also be useful in combatting multipath fading.

Factory channel impulse response measurements (also called power delay profiles) reveal that for LOS paths there typically exist only a few specular multipath components, with the direct path having a larger signal level than the latter components. Over obstructed paths, however, when either the transmitter or receiver is shadowed by large equipment or by stacks of inventory, the predominant energy arrives 50 to 150 ns after the first observable signal.

To determine how individual signal components change with receiver motion, 19 equally spaced power impulse response measurements were made along 1 m tracks throughout five factories. Figure 8 illustrates how specular reflections from perimeter walls, etc. are easily distinguishable. In Figure 9, typi-
One measure of multipath conditions is the RMS delay spread o of which is inversely proportional to the maximum usable data rates of a channel. RMS delay spread is computed as the square root of the second central moment of the delay spread values in factories do not depend on whether or not there exists an LOS path.

In Reference 21, it was shown that the coherence (flat fading) bandwidth over Rayleigh fading channels using DPSK modulation is approximately 1/50th of the reciprocal of RMS delay spread. For factory radio channels, this suggests worst-case maximum data rates of 33 kbps using simple receivers, with higher capacity coming about from distributed antennas, adaptive equalizers and diversity techniques. Recently, rapid changes in channel group delay have been found to cause burst error in digital communications systems due to shifts in eye pattern timing (22,23). This phenomenon, known as jitter, becomes increasingly important as operating bandwidths are increased while the fading rate of the channel remains small. Such a situation arises in an indoor radio communication system. In Reference 6, empirical measurements were presented that indicate that channel delay spread can change by as much as 180 ns over a few centimeters of receiver movement.

Conclusion

Extensive measurement, characterization and modeling of indoor factory radio channels have been carried out. The work here reveals that manmade noise is not a serious problem at frequencies greater than 1 GHz, and that fading characteristics are highly dependent upon local topography in the workplace. Shadowing data and large scale path loss models have been developed and form the basis for designing reliable narrowband indoor radio systems for portable communications and AGV control. Wideband measurements reveal that current technology limits data rates to about 50 to 100 kbps. While this accommodates current needs, it is anticipated that greater capacity will be required for the highly automated and flexible factories of the future. Ongoing work at Virginia Tech is aimed at developing robust wideband communication system designs for indoor radio communications.

References

7. T. Takeuchi, F. Ikegami, S. Yoshida, N. Kikuma, "Comparison of Multipath Delay Characteristic
**Figure 9.** Typical multipath power impulse responses computed as a spatial average of 19 measurements over a 1 m track.


---

**About the Author**

Dr. Ted Rappaport is assistant professor at the Bradley Department of Electrical Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061; Tel: (703) 231-6834. He is also president of TES Technologies.

---

**Analog Circuit Simulation**

*NEW IS_SPICE/386 On 386 PC's, $386*

Outperforms Workstations

Increases Speed by 200 - 500%

Circuit Size nearly Unlimted

Supports 80387, 80387, Wintel 11673167

SPICE, a worldwide standard for analog circuit simulation runs on all 8086 PCs in real mode as IS_SPICE, for only $95:00: Performs AC, DC and Transient, Noise, Distortion, Fourier and Sensitivity Analysis.