Photonic Applications in Wireless Terminal Networks

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ABSTRACT

Wireless communications are rapidly becoming the means of data and information transfer for a broad range of applications. As wireless communication applications continue to expand, the information transfer rates are evolving toward the Gigabit per second data rate and, for some applications, there is even a need for terabit per second data rate transfer in the wireless network. In addition, wireless terminals often require instantaneous switching and communications between network members. For most applications directional antennas are needed to support the high data throughput requirements, and phased array antennas are the only high gain, directional antennas that can be rapidly switched to provide instantaneous communications among network members scattered geographically. Wireless terminal equipment is currently designed to operate in the 1 to 60 GHz frequency range and, traditionally, these equipment are designed with RF hardware. More recently, optics technology has been demonstrated to play an important role in RF systems as the True-Time-Delay in the phased array antenna, and, for some systems operating at high data rates, optical interconnects at the baseband level require E-O and O-E conversions. This paper discusses the considerations in using optics technology in the design of the wireless terminal network including optical signal processing, optical backplanes, optical networking, optical interconnects, and optical components. This paper also describes the architecture of an RF wireless communications network using a range of optical technologies.

Key words: Photonic RF, communication network, optical interconnection, optical signal process

1. INTRODUCTION

RF data link communication systems are not strictly defined as a particular communication system. A data link communications system is normally thought of as a communication system that is designed to reliably transfer digital data, normally at high data rates to insure the data can be processed or used real time. In addition, these data link communication systems are normally associated with high value data, such as sensor and imagery (video) for reconnaissance, where the link reliability is very important. For example, the Royal Air Force requirements for airborne reconnaissance capabilities include near real time day/night, all weather, reconnaissance capability based on a mix of visible and IR electro-optic sensors and synthetic aperture and moving target indication radar sensors\textsuperscript{1}. The implementation of this data link requires a very high data rate for real time data transfer and a reliable transmission link to insure the reliable transfer of this valuable, time-critical data. In addition, these data link systems normally include a significant amount of Forward Error Codes (FEC) to insure that any bit-errors in the data as a result of the communications link are corrected to provide an output data stream that is basically error free.

RF data link equipment is often unattended and can undergo significant environmental changes. For this reason and others, the equipment is often designed to operate in an extreme range of environmental conditions. Data rate requirements in the tens of megabits require operating frequencies in the 10-40 GHz range and RF power amplifiers up to 100 watts of RF power. These requirements often result in a design that is relatively heavy and for some applications requires liquid cooling. An RF unit of a qualified data link terminal in ATR packaging (L=24.84", W=10.12", and

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antennas. Also, this requires each of the terminals to totally demodulate (or modulate) and process the RF signal to baseband before handing the information over to the controller or another terminal located on the aircraft. Another architecture alternative would be to have all of the terminal equipment located together within the aircraft and then feed each of the antennas with the RF signal from a central source. In this way all signal processing and control could be accomplished in one location. This approach is complicated by the remote location of the antennas from the centralized terminal system. For a system using multiple antennas and where high data rates need to be readily exchanged among the terminals (up to hundreds of megabits per second), there needs to be a range of operating frequency bands available to insure reliable communications and minimize the potential of interference. Dish antennas with conventional waveguide feeds are somewhat restricted in the range of operating frequencies. Phased array antennas are evolving toward a broad operating frequency range capability. The exact design of each phased array antenna used in a multiple antenna network would depend on a wide range of system requirements and constraints.

Phased array antenna designs vary considerably, and there are a number of designs that could be used to meet the requirements of a multiple antenna network. Individual receive and transmit antennas could be used. Although the antenna design would be simplified as compared to a full-duplex phased array, using the individual antennas could require more antennas, and would impact the installation on the aircraft. There are a host of considerations and tradeoffs in the phased array antenna design that will greatly affect system performance, including the transmit EIRP, the equivalent parabolic dish size and receiver noise figure, the scan angle of the beam, and flexibility in frequency bands of operation.

The multiple antenna network could include a range of member types; members who normally operate with other networks or operate independently. Because of this range of users and the need to provide communications when requested, there would need to be a range of operating frequency bands. An ideal system would be capable of operating in a number of frequency bands with the capability of rapid switching among the frequency bands. The X-band (10 GHz) and Ku-band (15 GHz) frequencies are ideal for utilizing the existing state-of-the-art phased array antenna design technology, although these frequency bands are becoming congested. Expanding the network to include operation in the 21.5 GHz to 22.5 GHz, 26.5 GHz to 27.5 GHz, and the 36 to 37 GHz frequency bands would greatly enhance the flexibility of the system.

One possible design of a phased array antenna to meet the requirements of the multiple antenna networks would be:

1. Provide operation in any of the frequency bands described above.
2. Provide beam scanning of plus and minus 30 degrees.
3. Provide an interface with the optical fiber from the terminal to recover the RF signal from the fiber at a nominal 10-dBm power level.
4. Provide an interface with the control cable from the terminal to provide rapid beam switching.
5. Provide full duplex operation in any of the frequency bands (X-band, Ku-band, 21.5 GHz to 22.5 GHz, 26.5 GHz to 27.5 GHz, and 36 to 37 GHz) with 300 to 500 MHz of frequency separation between transmit and receive.
6. Provide sufficient EIRP to close the link with a companion terminal (ground terminals to have parabolic dish antennas).
7. Provide sufficient antenna gain and receiver noise figure to close the link from companion terminals.
8. Provide one RF interface to the terminal for transmit and receive.
9. Provide an overall antenna design that is feasible for operating at any of the required frequency bands.

### 3. OPTOELECTRONIC INTERCONNECTS

To successfully use optical technology to augment the design of RF hardware and other electronic designs not only requires an optical design that provides an attractive alternative to the conventional electronic hardware alternatives in terms of performance and cost, but also requires an interface with the electronic hardware that does not add complexity to the overall design. Ideally, this interface would be relatively simple. In 1991 Taylor, et al reported a monolithic fabrication sequence consisting of eight masking levels for the two circuit configurations shown in Figure 1. Taylor, et
described a monolithic integration of lasers with HFETs and bipolar transistors in 1993. Figure 2 shows the device cross section for the integrated structure. This monolithic integration of the electronic and optoelectronic components is a key in achieving a low cost and providing an efficient interface between the electronic and photonic technologies.

![Circuit Configuration - Integrated laser/HFET and Integrated laser/bipolar Amplifier](image1)

The novel method of integration described by Taylor would not only provide an efficient interface between the electronic and optoelectronic circuits, but also has the potential to amplitude modulate the laser and, therefore, provide a means of transferring most, if not all, of the RF frequencies in the radio.

### 4. DETECTOR-SWITCHED OPTICAL TRUE-TIME-DELAY LINES

Optical technology for use as the True-Time-Delay (TTD) in phased array antennas is a significant change in the design approaches for this function. The alternative (and the more conventional) phase shifter technology has a relatively narrow bandwidth and a fairly high insertion loss. This insertion loss increases significantly as the operating frequency increases. The optical TTD has the potential for a significant improvement in operating bandwidth. Among the enabling technologies that need to be developed is a modulator that can transfer the RF signal to the optical domain and a photodetector that detects the RF signal, without either distorting the RF signal.
The feasibility of the optical technology has been demonstrated using an ultra long photonic polymeric channel waveguide circuit on a semiconductor substrate, with a high-speed photodetector array. The photonic polymeric waveguide circuits were made up of polymeric channel waveguides, waveguide grating couplers, and waveguide amplifiers. With this implementation, the polymeric waveguide circuit was capable of providing optical true-time-delays from 1 ps to 50 ns for wideband multiple communication links in a compact miniaturized scheme. The bandwidth of this approach was limited by the bandwidth of photodetectors to around 60 GHz. The optical amplification along the waveguide propagation is important to compensate for the optical loss due to the waveguide propagation loss and grating fanout loss. A large number of true-time-delay combinations could be generated simultaneously using this technique, by electronic switching the photodetector array fabricated under the polymeric waveguide circuits. Unlike any conventional approach where one TTD line can provide only one delay signal at a time, this true-time-delay module is capable of generating all required optical true-time-delay signals simultaneously to all antenna elements.

5. RF SPECTRUM CONVERSION CONSIDERATIONS

Direct conversion of the microwave RF spectrum onto a fiber optic link allows the spectrum to be readily moved to other locations without encountering the losses associated with coaxial cable or waveguide. For a RF photonic link, RF signals would be converted to the optical domain and transported in the optical domain. The RF signal would then be recovered from the optical domain by a detector. While conversion from an RF to an optical domain can have a number of benefits, cross-connection problems also require consideration of added distortion to the RF signal that might result from the conversion of the RF to the optical domain, transport in the fiber, and conversion back to the RF domain. In addition, the amount of noise that might be added to the RF signal during this process has to be considered. For RF signals such as phase modulation, any distortion would most likely cause the bit errors in the receiver. Ideally, this conversion to the optical domain should not result in any distortion to the RF spectrum. The present design of these systems requires a transimpedance amplifier to compensate for the mismatch in impedance from the 50 Ohm RF system to the nominal 10 Ohm laser diode. The laser diode also has limited dynamic range, which would require the RF signal level to be maintained at acceptable power levels. Performance is very important but the cost of the fiber optic link is also important.

For analysis the characteristics of E-O conversion, optical fiber transmission and O-E conversion with respect of the performance to the RF photonic links can be considered. Among the many considerations in evaluating the performance parameters of a RF photonic link are the bandwidth, RF link gain, link linear dynamic range, and noise figure. For most applications, phase linearity, group delay, and amplitude conversion to phase distortion are also concerns. An optical link is generally designed to meet stringent requirements on spectral purity to achieve good system performance. The goal of the designer of the optical link would be to minimize the degradation of the microwave signal by maintaining spectral purity, especially in terms of minimizing phase noise.

IM-DD (Intensity Modulation and Direct Detection) is the common modulation in fiber systems for digital and analog applications. The transfer function of an optical fiber with a length of \( z \) can be described as follows:

\[
H_f(\omega) = C_{IM-IM}(\omega) + \frac{H_{PM}(\omega)}{2} C_{PM-IM}(\omega)
\]

(1)

where \( C_{IM-IM}(\omega) \) and \( C_{PM-IM}(\omega) \) are the IM-IM and PM-IM conversion functions, respectively, and \( H_{PM}(\omega) \) is the (small-signal) transfer function of the relation between IM and PM for a given transmitter. Dispersion, loss, and nonlinearity of optical fibers can be reflected and analyzed using the above general expression.

The dispersion and nonlinearity of fiber may, in certain scenarios, strongly enhance the conversion between the intensity modulation (IM) and the phase modulation (PM) of the optical carrier. However, if we neglect the influence of loss and nonlinearity, we can get a simplified form:
\[ C_{M-\text{li}}(\omega) = \cos\left(\frac{\beta_2 \omega^2 z}{2}\right) \]

\[ C_{P\text{M-li}}(\omega) = 2 \sin\left(\frac{\beta_2 \omega^2 z}{2}\right) \]

where \( \beta_2 = \frac{\lambda^2 D}{2 m c} \), with D being the dispersion parameter of optical fiber.

**LD (Laser Diode) direct modulation is a simple technique to generate a RF signal in an optical system.** However, to avoid the nonlinearity of LD, external modulation with an M-Z (Mach-Zehnder) modulator, an EA (electroabsorption) modulator, or possibly a directional coupler modulator could be used. Heterodyning is another method that could be used to generate a RF signal in an optical system. Optical heterodyning using a square-law photodetector generates a mm-wave having the frequency equal to the beat frequency between the two lightwaves. One way to minimize the phase noise contribution to the mm-wave is to ensure that the phases of two lightwaves used in the heterodyning process be correlated. For this there are two approaches: one is to use V_e-biased electro-optic modulator, and the other is to use a MLLD (Mode Lock Laser Diode). Freedom from the fiber dispersion effect and full modulation depth is inherent in the MLLD scheme.

There are a number of schemes that can be used to avoid response fading of the DSB signal in fibers, to mitigate the influence of dispersion and nonlinearity on the two sidebands of the modulated lightwave\(^7\). Analysis and experimentation show that the SSB signal has better performance characteristics and can pass the signal, although some ripples occur which will distort the signal and cannot be removed completely\(^8,9\). Optical down conversion to the RF domain is affected by low-mixing efficiencies and high-noise figures when compared to the traditional microwave mixers. There is work underway to improve the performance of this part of the optical link\(^10\) and to improve its overall performance characteristics.

For many applications the complex structure of the RF signal has already been generated and merely needs to be converted to the optical domain, as needed, and then converted back to the RF domain with the necessary time delay. An implementation of this type has been developed and is on the market\(^11\). It provides a fiber-optic link to replace coaxial cables for RF signals from 1 to 11 GHz. The design approach for this product provides the basic architecture for similar designs and provides an interface between a RF system and an optics system (50 ohms for RF to 10 ohms for a laser diode). It also provides a suitable dynamic range that will meet the requirements for a variety of RF applications and addresses the noise figure problem, which could contaminate the RF signal.

### 6. BACKPLANE

There has been much work in the development of backplanes. For conventional backplanes, the design has become somewhat mature and is approaching the electrical limits of backplane technologies. The recent design efforts are targeted to reduce cost, increase reliability, and provide a design that minimizes coupling between layers and thus reduces the probability of interference. Integrating photonic technologies into the backplane could expand the capabilities of the backplane and change the architecture of the overall design.

There are a host of companies working on the development of the optical backplane. There are a few technologies available for implementation of optical backplanes. The fibers and planar waveguide approaches are basically point-to-point interconnects, and the signal broadcasting is difficult, which is a significant disadvantage in processing applications like computers, but may be very acceptable for high speed signal transfer in data link applications. An alternative optical technology is the free-space optical interconnects approach, such as COSINE-I, II, and III. This approach offers a flexible distribution scheme with comparatively fewer physical contact points on the board region. However, free space approaches suffer from reliability issues due to the difficult alignment requirements and environmental issues, such as air turbulence and moisture, that are probably inevitable in some of the data link radio applications. Another alternative is
the proprietary Radiant Photonics substrate guided-wave optical backplane approach. With this method the optical path is defined by total internal reflection within the plane-parallel glass plates, which inherently combines both previous alternative's features and avoid their pitfalls.

The objective of most of these development efforts is to develop an optical backplane that can transfer data at terabit data rates from any board in the chassis to any other board in the chassis. A related and important objective of the optical backplane design is to accomplish changes in the data flow at an extremely high data rate, such that there is no effect on the data during the routing process. The limited bus bandwidth is a problem for efficient high data rate communications among processing components, memory modules, and other I/O interface units. Optical schemes, in contrast to the conventional electrical backplane, minimize the constraints of signal propagation delay, skew, power consumption, and capacitive effects. Although the development of the optical backplane is not targeted for use in the high capacity data link communications equipment, many of the design features of the optical backplane design could be used in a hybrid backplane design, using optical features to augment the multilayer board normally used.

As the baseband data rates for the RF data link systems move toward the Gigabit data rate, optical implementation alternatives overlap the available conventional RF hardware implementations. In addition, for Gigabit data rates the baseband interfaces from external equipment could be optical as well as conventional RF interfaces. If the optical interface was selected as the standard interface, the conventional RF interface data could be multiplexed into the fiber to allow a single interface into the RF data link equipment. This multiplexing could be accomplished at the RF unit, and there are a number of design approaches that could be used for this implementation.

7. REMOTING RF SIGNALS

The conventional approach for connecting the antennas with the RF signals generated in the terminal equipment is to use waveguide or coaxial cable. For the operating frequencies outlined previously, waveguide and coaxial cable have a number of drawbacks. The mechanical configuration of waveguide restricts the operating frequencies. Table 1 describes the range of waveguide types required to service the operating frequencies.

<table>
<thead>
<tr>
<th>Waveguide Type</th>
<th>Frequency Range (GHz)</th>
<th>Attenuation</th>
<th>Inside Dimensions (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WR-90</td>
<td>8.20-12.40</td>
<td>4.3-3.0</td>
<td>0.900-0.400</td>
</tr>
<tr>
<td>WR-75</td>
<td>10.00-15.00</td>
<td>5.2-3.6</td>
<td>0.750-0.375</td>
</tr>
<tr>
<td>WR-62</td>
<td>12.40-18.00</td>
<td>6.5-4.7</td>
<td>0.622-0.311</td>
</tr>
<tr>
<td>WR-42</td>
<td>18.00-26.50</td>
<td>14-11</td>
<td>0.420-0.170</td>
</tr>
<tr>
<td>WR-28</td>
<td>26.50-40.00</td>
<td>23-16</td>
<td>0.340-0.170</td>
</tr>
</tbody>
</table>

To cover a frequency range from 8 to 40 GHz would require five different waveguide types. It would not be practical to have all five sizes routed to each antenna and then switch waveguide types for each of the frequency bands. Another consideration with the conventional waveguide is the attenuation. For a number of applications the antenna may well be restricted to operation in only one of the frequency bands. This would simplify the design, but the resulting attenuation within the waveguide would need to be considered. For many applications with dish antennas the RF power amplifier and the RF receiver pre-amplifier are mounted on the antenna. In this way any losses in the waveguide can be made up in those amplifiers. The restrictions are that the preamplifier gain is high enough to insures the receiver noise figure will not be degraded due to the loss in the waveguide. In addition, the gain of the RF power amplifier must be high enough to compensate for the waveguide losses.
Also, since waveguide is mechanical, the waveguide run needs to be mechanically supported. This most often requires the waveguide runs to be tailored, and this requires waveguide bends and joints. These runs not only increase cost but also result in additional power losses that would be considered in the overall system design.

An alternative to waveguide would be to use coaxial cable. Although coaxial cable is not adequate to cover the frequency spectrum of 8-40 GHz, for some applications at the lower frequencies with short runs of cable, the coaxial cable might be good enough. RF losses at the operating frequencies can be very high. Table 2 lists a number of coaxial cables that could be used for short runs at the operating frequencies. Notice that the RF losses become prohibitive as the frequency increases. Also, notice that the cutoff frequency for the coaxial cable does not cover the desired operating band, although there are coaxial cables that are designed to operate at higher frequencies. One cable does have operating characteristics up to 20 GHz, although the RF losses are extremely high at this frequency. For larger cables the RF losses are lower, but because the cables become physically larger, the frequency handling capability is reduced. Notice that 1/4" foam Heliax will operate up to 20 GHz but the performance characteristics for 1/2" foam helix are only provided to 10 GHz. For some application with the lower GHz frequencies the Heliax would probably be adequate for short cable runs.

An alternative to transferring the RF frequency spectrum on frequency is to convert the spectrum to a lower frequency, an intermediate frequency, such that the RF losses through the coaxial cable would not be as high. Even this could be a problem where the data bandwidth is very high and the intermediate frequency would also have to be high. This approach complicates the system design by requiring a frequency conversion at the control terminal and then another frequency conversion at the antenna. This increase in system complexity also results in a substantial increase in system cost.

<table>
<thead>
<tr>
<th>Coaxial Cable Type</th>
<th>Frequency</th>
<th>Attenuation Selected Frequency (dB/100 MHz/Frequency)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RG 142</td>
<td>8000 MHz</td>
<td>32 dB/5000 MHz</td>
</tr>
<tr>
<td>RG 213</td>
<td>1000 MHz</td>
<td>7.3 dB/1000 MHz</td>
</tr>
<tr>
<td>RG 223</td>
<td>12,400 MHz</td>
<td>24.8 dB/3000 MHz</td>
</tr>
<tr>
<td>SF 142</td>
<td>34,000 MHz</td>
<td>22.5 dB/3000 MHz</td>
</tr>
<tr>
<td>HS1RF-50A (1/4&quot;)</td>
<td>10 GHz</td>
<td>20.2 dB/10 GHz</td>
</tr>
<tr>
<td>HST2-50 (3/8&quot;)</td>
<td>13.4 GHz</td>
<td>18.4 dB/13.4 GHz</td>
</tr>
<tr>
<td>HJ4-50 (1/2&quot;)</td>
<td>10.9 GHz</td>
<td>11.7 dB/10.9 GHz</td>
</tr>
<tr>
<td>HJ4.5-50 (5/8&quot;)</td>
<td>6.8 GHz</td>
<td>4.75 dB/6.8 GHz</td>
</tr>
<tr>
<td>FSJ1-50A (1/4&quot;)</td>
<td>20.4 GHz</td>
<td>33.5 dB/20.4 GHz</td>
</tr>
<tr>
<td>FSJ2-50 (3/8&quot;)</td>
<td>13.4 GHz</td>
<td>18.6 dB/13.4 GHz</td>
</tr>
<tr>
<td>FSJ4-50 (1/2&quot;)</td>
<td>10.2 GHz</td>
<td>14.8 dB/10.2 GHz</td>
</tr>
</tbody>
</table>

*Andrew Heliax (air dielectric)  **Andrew Heliax (foam dielectric)

Using optical technology to transfer the RF spectrum to the antenna would require a modulation and detection technique that would transfer the 8-40 GHz signals to the optical domain (the laser) without resulting in distortion to the RF signal. To best accomplish this would require a monolithic integration of a laser with an HFET or bipolar transistor. For example, the monolithic integration as described by Taylor, using inversion channel technology. In addition, this integration should include a readily adaptable interface to fiber cable.

8. CONCLUSIONS

As the digital data rate requirements increase to the Gigabit per second for high capacity data link systems, the application of the conventional RF technology overlaps the potential use of optical technology. This overlap in the technologies provides the opportunity for the designer to consider the use of optical hardware and other optical
techniques in the design of the next generation of high capacity RF data link systems. Phased array antenna technology continues to evolve and with the potential to operate anywhere in the 8-40 GHz frequency band; and the use of the conventional RF cables and waveguide feeds become inadequate to cover the operating frequency band. At these very high data rates the interfaces can be fiber cables and there would be a need for the baseband interface of these high capacity data link systems to interface with optical interfaces. Photonics has the bandwidth to cover much of the 1-60 GHz frequency spectrum. There are a number of evolving technologies could potentially accommodate the transition of the RF spectrum to the optical domain to take advantage of photonic performance characteristics. For example, the technology to monolithically integrate HFET and bipolar transistor with a laser, and to readily accomplish the optoelectronic interface provides some promise that RF signals can be transferred to the optical domain for transmission to other locations without encountering the RF insertion losses associated with the use of waveguide and coaxial cable. There are a host of factors that need to be considered in this evolving technology including cost, complexity, and distortion to the RF signal during the various processes.

REFERENCES