Fiber-wireless networks incorporating wavelength division multiplexing

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ABSTRACT
Broadband wireless access operating in the microwave and millimeter-wave frequency windows has been actively investigated for future ultra broadband communications. The drastic increase in the throughput of each base station in these systems necessitates the use of an optical fiber backbone to provide broadband interconnections between the central office and all the antenna base stations. With such a network layout, significant reduction of the antenna base station complexity can be achieved by moving the routing, switching and processing functionalities to the central office. By taking advantage of optical networking techniques such as wavelength division multiplexing (WDM), the total capacity of the hybrid fiber-wireless network can be greatly enhanced and efficient optical fiber architectures can be realized. In this paper we present an overview of the research that has been carried out in fiber-wireless networks incorporating WDM, with a particular focus on the optical interfaces in such networks.

1. INTRODUCTION

Fixed wireless access at millimeter-wave (mm-wave) or sub-millimeter-wave frequencies has the attractive feature of providing users with seamless connectivity [1]. With the inherent high propagation loss characteristics of radio signals at these frequencies, pico- or microcellular architectures are essential to provide efficient geographical coverage. To accommodate such an architecture, a large number of antenna base stations (BSs) have to be deployed to optimize the antenna coverage. It is therefore essential to simplify the antenna BS by moving all routing, switching and processing functionalities to the headend, thereby enabling the cost and equipment to be shared among all the base stations. With the coverage zone of each antenna BS greatly reduced while the throughput has been significantly increased, optical fiber backbone with its inherent low loss and large bandwidth characteristics has proven to be an ideal transport medium.
Shown in Fig. 1 is a typical hybrid fiber-wireless scenario incorporating optical networking technology such as wavelength division multiplexing (WDM). Here an optical headend or central office (CO) acts as the gateway to the optical WDM backbone while serving a large number of widely distributed antenna base stations. The last mile distribution is via broadband wireless at mm-wave frequencies. One of the technical challenges in the deployment of such a hybrid network lies in the realization of functionally simple, compact and low-cost antenna BSs. It has been widely shown that transporting the radio signals at mm-wave frequencies has the potential and advantage of reducing the complexity of the antenna BS by moving most of the hardware intelligence to the CO, thereby realizing a centralized control architecture. However the optical transportation of radio signals at mm-wave frequencies is subject to severe fiber dispersion penalties [2], although it has been shown that it can be somewhat overcome with the use of an optical single sideband with carrier (OSSB+C) modulation scheme [3].

In addition to helping to mitigate RF power penalties, the OSSB+C modulation scheme improves the optical spectral usage by at least 50%. Nevertheless the transportation of OSSB+C modulated radio signals at mm-wave frequencies still leads to the inefficient use of the optical spectrum especially in a WDM environment where the actual information bandwidth of the radio signals modulated onto an optical WDM channel (typically at 50 or 100 GHz spacing) is < 2 GHz. Wavelength-interleaving (WI) has been shown to be able to improve the optical bandwidth usage by threefold using OSSB+C [4]. This technique enables multiple mm-wave radio signals to be multiplexed in such a way that the optical channel spacing between adjacent WDM channels is less than the mm-wave radio frequency [5,6]. The successful implementation of such wavelength-interleaved dense WDM (WI-DWDM) feeder networks in mm-wave fiber-radio systems however, is largely dependent on suitable and effective multiplexing and demultiplexing. In this paper, we review the different technologies for multiplexing and demultiplexing schemes to realize a highly spectral efficient WI-DWDM fiber-wireless network.

With the incorporation of WDM in RF fiber-wireless approaches, a fast deployment route for these systems may be achieved. By leveraging the optical network infrastructure already existing in the access and metro network domains, unused fibers may be utilized as the means of communication between the CO and the BSs. It is therefore equally important that RF fiber-radio access technology can coexist with other optical access technologies; being able to merge/integrate within the existing infrastructure and ensure transparency in the remote access nodes (RNs). We will review a hybrid multiplexing scheme that we have recently proposed and demonstrated, that has the capability to multiplex optical millimeter-wave, baseband, and intermediate frequency signals. The proposed scheme enables the convergence of ‘last mile’ wireless and wireline technologies, leading to an integrated DWDM network in the access and metro domains.

2. WDM WAVELENGTH-INTERLEAVED FIBER-RADIO SYSTEM

Fig. 2 shows a schematic of a WDM fiber-wireless architecture with a primary ring and incorporating both wavelength-interleaving and OSSB+C modulation schemes. In such a configuration, an optical interface capable of dropping and adding the dense-WDM WI channels is essential at the antenna BS [7]. We have recently demonstrated a multi-functional BS optical interface that supports optical adding and dropping of WI-DWDM channels from the main trunk, while removing the need for an optical source within the BS. Shown in Fig. 3 is the optical interface based on a 7-port optical circulator in conjunction with a double notch and a single notch fiber Bragg grating (FBG). The interface consists of ‘IN’, ‘OUT’, ‘DOWNLINK DROP’, ‘λ-REUSE’ and ‘ADD’ ports. Here three RF channels at 37.5 GHz are interleaved such that the spacing between the optical carrier and the adjacent sidebands, which enter the optical interface via port 1 (IN), is 12.5 GHz. The double notch filter at port 2 reflects 100% of the desired downlink optical carrier (λ2 in this case) and its corresponding sideband, while transmitting the ‘thru’ channels to port 6 of the circulator which are routed out from the interface via port 7 (OUT). The FBG at port 3 was designed to reflect 50% of the optical carrier at λ2 while the remaining 50% of the optical carrier and the corresponding sideband are dropped at port 3 (the DOWNLINK DROP). The 50% of the reflected optical carrier at λ2 is recovered at port 4 (λ-REUSE) and can be reused as the uplink optical carrier through being modulated by the upstream mm-wave radio signals [8]. The uplink optical signal can be added back to the main stream via port 5 (ADD) and combines with the ‘thru’ channels and exits via port 7 (OUT).
Fig. 2  Schematic diagram of a WDM fiber-wireless ring architecture incorporating OSSB+C modulation and wavelength-interleaving schemes

Fig. 3  Multi-functional WDM optical interface with optical add-drop and wavelength re-use functionalities
3. SIMULTANEOUS MULTIPLEXING AND DEMULTIPLEXING OPTICAL INTERFACE

The multi-functional optical interface with add-drop capability introduced in Section 2 is an ideal passive optical add-drop multiplexer in the antenna base station, especially in a ring architecture. However in a star-tee architecture, an optical interface with simultaneous demultiplexing and multiplexing of several channels is essential in the CO and RNs of the fiber-wireless network. In such an environment, a series of cascaded optical interfaces demonstrated in Section 2 would be needed which could impose significant performance degradation and limitations in the network dimensioning. Furthermore a series of cascaded interfaces also leads to complex, bulky and expensive demultiplexing/multiplexing subsystems. It is therefore essential to combine these functionalities required in the CO and RNs into a single device whereby cost-effective architectures with reduced complexity can be realized. In addition, it is equally important that passive WDM components in the COs and RNs are transparent to the uplink channels generated by reusing the downlink optical carrier, which allows the BS to be simplified by removing the light source from the uplink path [8].

Simple multiplexing schemes that efficiently interleave DWDM mm-wave fiber-radio channels separated at 25 GHz were proposed in [9 – 11]. A demultiplexing scheme for 25 GHz-separated DWDM mm-wave fiber-radio channels was also proposed in [12], however this scheme requires additional wavelength-selective pre- and post-processing hardware, in addition to custom-developed arrayed waveguide gratings (AWGs). Recently, we demonstrated a simultaneous multiplexing and demultiplexing (MUX/DEMUX) scheme for the CO and the RN in a star-tree fiber-wireless system, which effectively multiplexes and demultiplexes 37.5 GHz-band WI-DWDM mm-wave fiber-radio channels spaced at 25 GHz [13]. The incorporation of such a scheme in WI-DWDM mm-wave fiber-radio systems can offer efficient multiplexing with improved overall link performance due to a reduction in carrier-sideband-ratio (CSR) [14]. In addition, the proposed scheme ensures the transparency of the CO and the RN to uplink (UL) channels generated by the downlink (DL) optical carriers, which enables a simple, compact and low cost BS through the complete removal of the UL light source. Fig. 4 shows a schematic of the optical spectra of N optical mm-wave channels before and after interleaving, with a DWDM channel spacing and mm-wave carrier frequency of 2\(\Delta f\) and 3\(\Delta f\), respectively. The optical carriers \(C_1, C_2, \ldots, C_N\) and their respective modulation sidebands \(S_1, S_2, \ldots, S_N\) (in OSSB+C modulation format) are interleaved in such a way that the adjacent channel spacing, irrespective of carrier or sideband, becomes \(\Delta f\).

![Fig. 4 Schematic depicting the optical spectra of the wavelength-interleaved DWDM mm-wave fiber-wireless channels](image)

Fig. 5(a) shows the schematic of the novel MUX/DEMUX scheme that simultaneously enables multiplexing and demultiplexing of the proposed WI technique. The MUX/DEMUX comprises a \((2N+2) \times (2N+2)\) AWG with a channel bandwidth \(\leq \Delta f\) and a channel spacing of \(\Delta f\), in conjunction with multiple optical circulators (OCs) and optical isolators (OIs). The input (A) and output (B) ports of the arrayed waveguide grating (AWG), reciprocal in nature, are numbered from 1 to 2\(N+2\). The characteristic matrix of the AWG that governs the distribution of different channels at various ports is tabulated in Fig. 5(b). For clarity the proposed scheme is considered to be located at a RN where the UL channels are multiplexed and the DL channels are demultiplexed simultaneously. As shown in Fig. 5(a), the DL WI-DWDM channels from the feeder network enter the RN, are split by a 3 dB coupler, and pass through circulators OC\(_{D1}\) and OC\(_{D2}\) before entering the AWG via the ports A\(_1\) and A\(_4\). The input ports, A\(_1\) and A\(_4\) were selected in such a way that the optical carriers \(C_{D1}, C_{D2}, \ldots, C_{DN}\) and their respective modulation sidebands \(S_{D1}, S_{D2}, \ldots, S_{DN}\) are demultiplexed together and exit the AWG via the odd-numbered output ports B\(_1\) - B\(_{2N+1}\) followed by OC\(_{M1}\), \ldots, OC\(_{MN}\), respectively.
circulators OC_{D1}, OC_{D2}, and OC_{M1}...OC_{MN} work as the means for combining/separating the DL and UL channels to/from a specific port of the AWG, and routing them to the destination accordingly.

In the UL direction, OSSB+C modulated optical mm-wave channels (S_{U1}, C_{U1}), (S_{U2}, C_{U2})..(S_{UN}, C_{UN}), generated by either using the optical carriers that correspond to wavelengths spaced at multiples of the Free Spectral Range (FSR) of the AWG from the DL optical carriers, or by reusing the DL optical carriers recovered by applying a wavelength reuse technique (\lambda_{UL} = \lambda_{DL} \pm n \times FSR, where n = 0, 1, 2, 3...etc.), are applied to the AWG via the ports B_{1} - B_{2N-1} followed by the circulators OC_{M1}...OC_{MN}. Due to the reciprocal and cyclic characteristics of the AWG, the UL optical carriers and their respective modulation sidebands combine at ports A_{4} and A_{1}, respectively. The composite UL carriers C_{U1}, C_{U2}...C_{UN} at A_{4} are then passed through OC_{D2} and looped back to the AWG through port B_{1} that redistributes the carriers respectively to the odd-numbered A_{3}, A_{5}, A_{7}...A_{2N-3} ports, starting with A_{3}. To realize the desired interleaving for the UL channels, the distributed UL carriers C_{U1}, C_{U2}...C_{UN} are again looped back to the AWG via the even-numbered B_{5}, B_{6}, B_{8}...B_{2N-2} ports, starting with B_{5} and the resulting outcome comprises the UL carriers and their respective modulation sidebands interleaved at port A_{1} (similar to the spectrum after multiplexing, shown in Fig. 4), which are then routed to the fiber feeder network via the OC_{D1}.

In Figure 5, the multiple loop-backs of the UL carriers through the AWG reduce the CSR of the interleaved UL channels by as much as twice the insertion loss (2 x IL) of the AWG (typically 4 – 5 dB), which is 8 – 10 dB. To minimize the effects of the unwanted signals from the even-numbered ports, B_{a} to B_{2N+2}, the loop-back paths of the redistributed optical carriers were provided with directional optical isolators that route only the redistributed UL carriers to the AWG and suppress the remaining unwanted signals. Thus, the proposed simultaneous multiplexing and demultiplexing scheme enables efficient multiplexing for the WI-DWDM mm-wave channels in the UL direction, while in the DL direction the circuit also demultiplexes the WI-DWDM channels very effectively.

![Proposed DEMUX/MUX Scheme](a)

![Characteristics Matrix of 2N+2 x 2N+2 AWG](b)

**Fig. 5** Simultaneous multiplexing and demultiplexing of wavelength interleaved channels in a DWDM mm-wave fiber-radio network: (a) the proposed DEMUX/MUX scheme, and (b) the input-output characteristic matrix of the AWG

### 4. WDM BASED HETEROGENEOUS ACCESS NETWORK

With various last mile solutions emerging, it is essential for RF fiber-wireless access technology to coexist with other optical access technologies, thereby being able to merge/integrate within the existing infrastructure and ensure
transparency in the remote access nodes. To realize an integrated optical access infrastructure simultaneous modulation techniques have been proposed [15,16] which enable baseband (BB), IF and RF technologies to be combined together in the remote access networks (RANs). However, the performance of these methods has been limited by the nonlinearity as well as the optimum modulating conditions of the modulators. Also, these techniques require significant changes both in the existing mini switching centers (MSCs) and the RANs. An alternative approach to realizing an integrated DWDM network in the metro and higher network domains is to incorporate a number of MSCs suitable for the role of a CO feeding clusters of BSs that service the RF fiber-radio system [17]. This technique has the limitation of requiring a dedicated optical network in the access domain. However, if the passive WDM components (e.g. multiplexers, demultiplexers, OADMs) in the existing MSCs and ANs can be provisioned instead to support RF as well as other conventional BB and IF access technologies thereby avoiding significant changes in the existing setup, an effective integrated optical access network can be easily realized. Shown in Fig. 6 is the schematic of an integrated optical access incorporating RF, BB, and IF in a WDM environment highlighting the merging of wireless and wireline optical access applications.

We have proposed and demonstrated a hybrid multiplexing scheme that effectively multiplexes the optical RF, BB and IF signals in a DWDM access network [18]. Fig. 7 shows the optical spectrum of the proposed multiplexing scheme comprising N channels for each of the RF, BB and IF signals, with a DWDM channel separation of $\Delta \lambda$. The RF carrier frequency is an integer multiple of the DWDM channel separation ($\lambda_{RF} = n \times \Delta \lambda$, where $n = 1, 2, 3, \ldots$), for instance, $3\Delta \lambda$. The signals are multiplexed in such a way that after multiplexing, the adjacent channel spacing, irrespective of RF, BB or IF signals, is $\Delta \lambda$. Fig. 8 depicts the configuration of the proposed multiplexing scheme that realizes such a hybrid multiplexed spectrum with the input and output spectra shown in the insets. It consists of a $(4N+1)\times(4N+1)$ AWG with bandwidth $\Delta \lambda$ equal to the adjacent channel spacing of the desired multiplexing scheme. The input (A) and output (B) ports of the AWG are numbered from 1 to $4N+1$. The optically modulated RF, BB, and IF input signals.
enter the AWG starting with port A2 to A4N, leaving the 5th, 9th, 13th,….(4N+1)th ports unused. The RF channels are modulated in OSSB+C modulation format. The AWG combines all the modulation sidebands S1, S2, …., Sn of the RF channels as well as the BB and IF channels at the output port B1. Due to the cyclic characteristics of the AWG, the optical carriers C1, C2, …., CN of the RF channels also exit as a composite signal via the output port B4. The composite carriers are then looped back to the AWG through the input port A1 that redistributes the carriers to the 5th, 9th, 13th, …., (4N+1)th output ports. To realize the desired multiplexing, the distributed carriers are again looped back to the AWG via the unused input ports and the resultant output at port B4 is the RF, BB, and IF signals multiplexed with the BB and IF channels interleaved between the optical carrier and the modulation sideband of the RF channels. The multiplexed spectrum can be seen in the insets of Fig. 8. As before, due to the loop-backs the optical carriers of the RF channels are suppressed by as much as twice the insertion loss of the AWG compared to the modulation sidebands. Thus the proposed multiplexing scheme enables a carrier subtraction technique that reduces the carrier-to-sideband ratio of the RF channels by 8 to 10 dB.

5. SUMMARY

We have provided a comprehensive summary and review of some of our research work in the area of fiber-wireless systems incorporating WDM networking techniques. The main focus of the research has been directed to the realization of highly efficient fiber-wireless network architectures that take advantage of WDM. The introduction of wavelength-interleaving and wavelength re-use techniques into the fiber-wireless network has further enhanced the overall optical spectral usage and also reduces the remote antenna base station complexity. We have discussed several optical interfaces suitable for a wavelength-interleaved DWDM fiber-wireless network that offers simultaneous multiplexing and demultiplexing capabilities. In addition, we have also explored the possibility of integrating fiber-wireless applications with other access platforms in a WDM environment.

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