Demonstration of Wavelength Packet Switched Radio-Over-Fiber System

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***Abstract*—The authors present a novel concept of employing optical wavelength packet switching in radio-over-fiber access networks. In such a system, the tunable laser (TL) would be employed as a transmitter in the central station. The optical carrier generated by this device would be externally modulated with the data signal upconverted to an RF frequency before being sent to the appropriate base station (BS). If each of the BSs is assigned a unique wavelength, the addressing and routing of traffic could be performed on a packet-by-packet basis with the TL switching between the wavelength assigned to different BSs.**

***Index Terms*—External modulation, fiber Bragg grating, optical packet switching, radio-over-fiber (RoF), tunable laser (TL).**

I. INTRODUCTION

AS THE demand for broadband mobile services such as video-on-demand increases, so does the need to develop high-capacity mobile communication networks such as the ultrawideband (UWB) systems and WiMAX standards. Although the application for these systems is primarily aimed at stationary users, their extension to low mobility scenarios is inevitable. Furthermore, as these systems are pushed to millimeter wave frequencies, the potential data rates increase into the gigabit per second range. Hybrid radio-over-fiber (RoF) systems are a very attractive option to realize such broadband networks—particularly for in-building deployments. In these systems, the millimeter wave signals are modulated onto an optical carrier at a central station (CS), and then distributed to remote antenna units (RAUs) using optical fiber [1]. As tunable laser (TL) technology advances, it is interesting to examine issues arising from using these RoF systems with a TL transmitter at the CS [2]. In such a configuration, the CS must implement some mobility management function to remember where each user is and provide electrical buffering of incoming data packets prior to scheduling the transmission. TLs can be used for sending each packet to the specific base station (BS) by transmitting on the wavelength assigned to that station (determined by bandpass filter at the BS).

The system used in these experiments employs a simple binary phase-shift-keyed (BPSK) modulation that is rather different from that used in real systems. The goal, however, is not to design a commercial radio system, but rather to investigate some fundamental issues. Although the experiments shown here only use three wavelengths, corresponding to three UWB zones in a building, it is expected that the low range of each RAU will lead to a requirement for 20 or more such zones in a modest office building. The single TL in this case then replaces 20 fixed wavelength devices and offers potential cost benefits and flexible, scalable upgrade routes.

In this letter, we introduce the concept of an RoF system employing wavelength packet switching (WPS) and examine the challenges of coordinating the wavelength switching and the transmission of the information packet. First, a simple system using a single TL is built and its performance is demonstrated. The basic TL properties and their impact on the system configuration are described. Next, the two-transmitter system and the cross-channel interference due to the TL wavelength instability and drift in a wavelength-division-multiplexing (WDM) WPS RoF network are investigated.

II. SINGLE TL SYSTEM—EXPERIMENTAL SETUP AND RESULTS

In the experimental setup shown in Fig. 1, a TL is set to switch between three wavelength channels, separated by 50 GHz, 35 (1550.865 nm), 36 (1550.465 nm), and 37 (1550.05 nm). The TL switches wavelength every 500 ns and sends a trigger signal to a pulse pattern generator. For the experiments, we used 350-ns data burst generated every 1.5 μs (the time over which the TL tunes through all three channels) and carrying 2.5-Gb/s data with a pseudorandom bit sequence (PRBS) length of $2^7 - 1$.

The burst data is passed through a low-pass filter (LPF) (to limit its spectral width) and mixed with a signal from a 20-GHz local oscillator (LO) to generate a BPSK RF signal. The RF modulated signal is then amplified and used to externally modulate the optical carrier (Channel 36). The data channel is then demultiplexed using an FBG with a bandwidth of 50 GHz in conjunction with an optical circulator. After photodetection, the data is down-converted using an electrical mixer and a signal from the LO, amplified and filtered using an LPF. The eye diagram is then displayed on an oscilloscope and the quality of the signal is verified.

The TL used in the experiments is a monolithic laser employing distributed Bragg reflector technology, which can tune between 80 channels with 50-GHz channel spacing. After each switching event, the laser output is blanked using a semiconductor optical amplifier to prevent spurious output from the TL causing a degradation of the WDM system performance [3]. The blanking time of the device is 60 ns.

The optical spectrum from the external modulator is shown in Fig. 2(a) and shows the time averaged signal with all three wavelengths present. In reality, each of these wavelengths are present one at a time and would require a time gated spectrum analyzer to separate them. It can be seen from the plot that even though the data is modulated only on Channel 36, all the channels have sidebands. This is due to the presence of the signal from the LO, which is continuously on so that it modulates the

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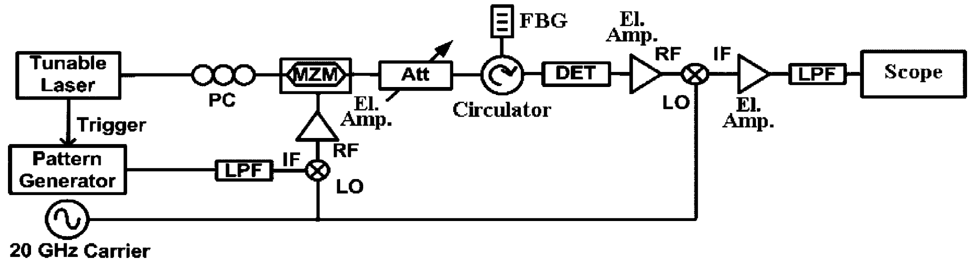

Fig. 1. Single transmitter RoF WPS system—experimental setup.

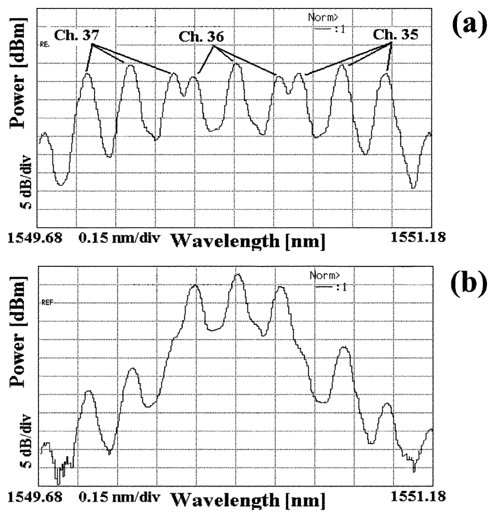

Fig. 2. Optical spectrum of the modulated TL switching (a) all three channels, (b) Channel 36 filtered.

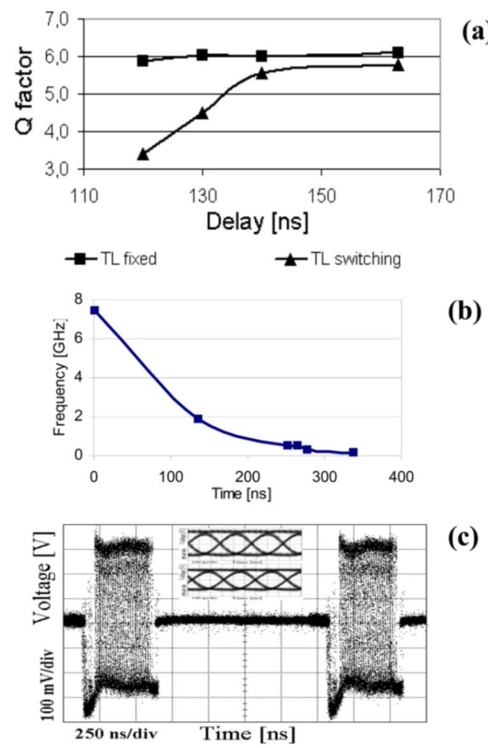

Fig. 3. (a) Q-factor versus delay of the packet start time; (b) frequency drift of the TL versus time; (c) received data packets.

Channel 35 and 37 carriers with a 20-GHz sinusoid. The optical spectrum of the demultiplexed Channel 36 is shown in Fig. 2(b).

In order to verify the performance of a WPS RoF system, we measured the Q-factor of the data signal as a function of the time that passed from the wavelength switch. The measurements were taken for the case when the laser was transmitting continuously on Channel 36 and when the laser was switching between the three channels. The results obtained are plotted in Fig. 3(a). From the figure, it can be seen that while the TL is not switching the Q-factor of the received data is around six. On the other hand, when the transmitter is switching between wavelengths, the Q-factor measured shortly after the end of the blanking time is very low and increases to its maximum value after 140 ns after the blanking of the laser is turned OFF. This variation in the quality of the received signal with time when the TL is switching is a result of the laser wavelength drift, which occurs as the device settles down at its destination wavelength after emerging from blanking. This drift has a dual effect on the received signal. First, as the wavelength drifts, the sidebands experience different levels of attenuation while passing through the OBPF, which results in a variation in power of the detected signal and a degradation of the signal-to-noise ratio in the demodulated data signal. Second, as the filter has a nonlinear phase profile at the edge of the passband, the wavelength drift also introduces a phase difference between the two sidebands, which results in intersymbol interference in the BPSK demodulator.

The laser frequency drift versus time (from the moment the blanking is turned OFF) was measured using a self-heterodyning method [4] and the results are shown in Fig. 3(b). It can be seen from the plot that when the TL emerges from the blanking time, its wavelength varies by around 10 GHz from the target value and this difference is reduced to 2 GHz after around 160 ns. Therefore, in order to avoid the degradation of information transmitted, the RF data packet should not be modulated onto the TL until its wavelength stabilises. In our case, this required delaying the packet by 140 ns to avoid the large transient after the end of the blanking period. Fig. 3(c) presents the oscilloscope traces of the received data packets with this 140-ns delay introduced. From the diagram, it can be seen that a large amount of noise is present in the signal just preceding the data packet. The inset of the Fig. 3(c) shows the received eye diagrams when the laser is fixed at Channel 36 and when it is switching between three wavelengths. It could be seen that as long as the 140-ns delay is introduced, there is no power penalty between both modes of operation.

In the system presented here, the 140-ns guard time corresponds to 350 bits and the packet duration corresponds to a payload of 900 bits, yielding an overhead of 28% for the time when no transmission is possible. Although this represents a signifi-

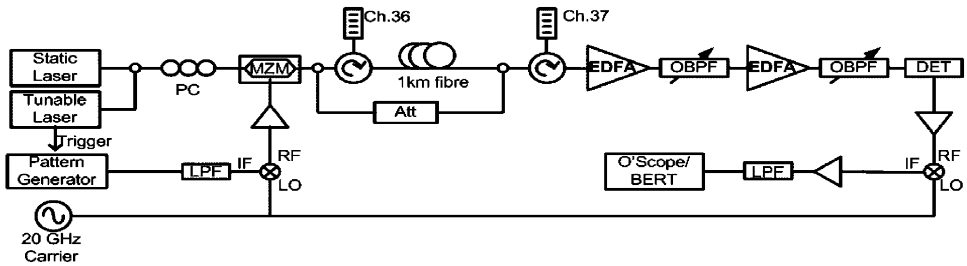

Fig. 4. WDM WPS RoF system—experimental setup.

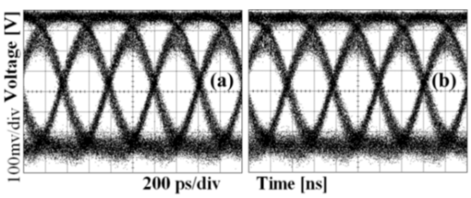

Fig. 5. Scope trace of the received data (Channel 37) with TL. Top: enabled; bottom: disabled.

cant overhead (these packet sizes were used to simplify the test setup), it seems more likely that packets will be typical Ethernet sizes of 12 000 bits, giving packet duration of 4.8 μs. This would yield an overhead of only 7% for a real deployment with this TL. It is reasonable to expect that advances in TL technology will reduce the guard time and therefore reduce the overhead further.

III. Two-Laser System—Experimental Setup and Results

In order to verify the usefulness of TLs in a WDM WPS RoF network, the system comprising two lasers was investigated using the experimental setup shown in Fig. 4. In this case, one TL and one static laser were coupled together and then externally modulated with a 2.5-Gb/s data signal BPSK modulated on a 20-GHz LO. The TL was switched between Channel 30 (1552.8 nm) and Channel 36 and the static laser was set to transmit on Channel 37. The static laser was then demultiplexed and the Q-factor of the received data was measured. Because both lasers were carrying the same data, it was necessary to decorrelate the signals by filtering Channel 36 (from TL) and sending it over an appropriate length of fiber, before recombining it with the fixed laser (Channel 37).

The scope trace showing the received data packets when the TL was switching (a) and turned OFF (b) are shown in Fig. 5. From the diagrams, it can be seen that there is no noticeable difference in the quality of the signals received. In order to verify this, the Q-factor of Channel 37 was measured at a number of points and no penalty was observed. This means that the wavelength drift was too small to cause any interference between the two channels carrying 20-GHz RF signals and spaced by 50 GHz. As the RF frequency increases, the distance between the sideband will reduce and the interference will increase. Nevertheless, it could be expected that RoF will portray a better immunity to wavelength drift of the TL than the systems carrying baseband data. This could be attributed to the fact that any portion of the signal (in our case from Channel 36) leaking through the passband of the optical filter will beat with the optical carrier (of Channel 37) to generate a different RF component than the desired signal. This component could then be filtered out using an electrical LPF at the destination (after the down-conversion of the RF signals). Further investigation of the complex interaction of a number of tuneable lasers would be required to fully characterise such a system and it would be expected that a slightly longer guard time would be required in such a scenario.

These tests have demonstrated that wavelength drift of the TL would pose a real problem only when it would cause the sidebands of the neighbouring channels to spectrally overlap. The design of such systems will need to consider the characteristics of the specific TL and will need to trade-off the wavelength spacing, the bit rate used, and RF carrier frequency required.

IV. Conclusion

A demonstration of an RoF WPS network was presented. The system employed a TL, which transmits data packets on different wavelengths depending on the destination BS. It has been shown that the wavelength drift of the TL needs to be taken into account when designing such a system. The results show that, for the specific setup used here, a 140-ns delay between the switching of the TL and the beginning of the data packet is required to optimize the performance of the system.

A two-transmitter system was also demonstrated and the influence of the TL wavelength drift on the neighboring channel was investigated. The Q-factor measurements show that there is not degradation in signal quality due to TL tuning. This proves that TL transmitters could be used in a WDM RoF system without causing interference and can enable possible new network architectures for broadband wireless deployments.

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