Inter-networking Hybrid Base Stations Towards the Convergence of Wireless and Wireline Access Networks

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1. Introduction

The demand for higher bandwidth necessitated by data-intensive multimedia and real-time applications is increasing in the access networks. To meet this bandwidth demand, a variety of access technologies are being introduced in the last mile access network, incorporating both wireless and wireline media. Among these solutions, passive optical networks (PONs) remain the most future proof technology for the delivery of broadband to users [1 - 3]. Radio-over-fiber (RoF) networks that can be categorized as the networking of wireless access points are very attractive for the delivery of broadband via wireless last mile solutions [4 - 6]. Carriers and service providers are seeking a convergent network architecture that can facilitate a rich mix of value added and differentiated services via a mix of wireless and wireline solutions to meet the demand for mobility, bandwidth and range of connectivity options for the customers [7, 8]. All of these requirements can be met by offering an integrated telecommunications package, for which an integrated access network that can support both wired and wireless last mile solutions is essential.

![Fig. 1: Generic integrated optical network architecture.](image)

A generic integrated network incorporating both wireless and wireline technologies are shown in Fig. 1. In the downlink direction, optically modulated wireless and wireline signals are transported from the central office (CO) to the remote access nodes (RANs), whereby the composite signal is divided either by a demultiplexer or a star coupler (SC) and distributed to the antenna base stations (BSs) and the optical network units (ONUs) for delivering to the customer units. In the uplink direction, the wireless and wireline signals from the customer units come to the RAN via the BSs and the ONUs, combined and transported to the CO. Therefore, to enable simultaneous transport of wireless and wireline services in the hotspots such as airports, shopping malls, and universities, both ONUs and BSs are needed to be co-located, which means multiple optical access points are required to cover the same geographical area. The requirements of multiple optical access points and the co-located BSs and ONUs can be avoided if the BSs can be enabled to support both of the wireless and wireline services. This paper proposes such a hybrid base station (H-BS) scheme that enables both the wireless and wireline services together. In addition, the proposed scheme is provisioned to establish inter-communications among the customers of the neighbouring H-BSs without sending the signal back to the CO, which is widely expected in the modern access networks, as future wireless devices in customer sites will also serve as routers to communicate in a multi-hop mesh network.

We have considered a few solutions for the architecture of the H-BS. One of the most important factors to be considered for the integrated access network infrastructure is the cost of the optical sources that are used at the H-BS. We have carried out experiments and analyzed and compared the performances with various optical sources such as reflective semiconductor optical amplifier (RSOA), vertical cavity surface emitting laser (VCSEL), and distributed feedback laser placed at the H-BSs to enable the transport of both Ethernet data to and from the H-BSs and RF signals amongst the H-BSs.
2. Hybrid Base Station Scheme using RSOA

Fig. 2 depicts the configuration of the proposed hybrid base station. It consists of a CWDM coupler, an RSOA, a photodetector (PD), a radiating antenna and electrical signal conditioning devices, in addition to a provisional 1x2 opto-mechanical switch (OSW) to establish inter-communication among the neighboring customers, bypassing the CO. Optically modulated downlink wireless (IF signal) and wireline (baseband Ethernet) signals and uplink optical LO carrier from the RAN come across the H-BS and separated by the CWDM coupler. The downlink signals are detected by the PD and divided into two parts by a 3 dB electrical splitter. The IF signal is separated from the Ethernet signal using an electrical bandpass filter (BPF) prior to its radiation to the customers via the antenna. The second part of the divided signal is sent through a lowpass filter (LPF) to separate the Ethernet signal, before it is plugged into the wall to feed the Ethernet hub. In the uplink direction, the uplink electrical signals from wireless and wireline customers are combined and modulated by the RSOA, which is driven by the uplink optical LO carrier from the CO. The use of RSOA enables source-free operation at the H-BSs and avoids lossy modulators to offer higher flexibility and high capacity upstream traffic. The modulated and amplified uplink signal from RSOA was then sent in the uplink direction. To support inter-communication among neighboring H-BSs, another optical receiving port, followed by a 1x2 OSW, is also provisioned to the scheme. This second receiving port can be connected to the RAN to receive the broadcast signal from the neighboring H-BSs, reducing the cost and complexity of the CO. Thus, the proposed H-BS has the potential to establish inter-communication among the customers of neighboring H-BSs, while effectively enables both the wireless and wireline signals, leading to an integrated network for the access and metro domain.

2.1 Experimental Demonstration

Fig. 3 shows the experimental setup to demonstrate the capabilities of the proposed scheme. A 2.5 Gb/s downstream signal of $2^{31}$-1 pseudo random ninary sequence non-return-to-zero (PRBS NRZ) data was modulated onto downlink carrier, $\lambda_D (= 1553.2 \text{ nm})$ using a Mach-Zehnder modulator (MZM) and combined with the remotely delivered uplink optical carrier, $\lambda_U (= 1591 \text{ nm})$ using a 3 dB coupler.
Although the downlink signal is expected to be a combination of baseband wireline and IF wireless signals, IF signal is discarded to avoid any verbosity, as the demonstration in the uplink direction considers both baseband and IF signals together. $\lambda_d$ and $\lambda_u$ were transmitted to the H-BS through a 10 km single mode fiber (SMF), a 4 x 4 SC and a 2.2 km distribution SMF. At the H-BS, $\lambda_d$ was separated from $\lambda_u$ using a CWDM coupler. The separated $\lambda_d$ was detected using a PD to measure the bit error ratio (BER) performance. In the uplink direction, a 1 GHz binary-phase-shift-keyed (BPSK) IF signal, which was generated by mixing with a 155 Mb/s $2^{31}-1$ PRBS NRZ data, was electrically combined with a 750 Mb/s baseband signal of $2^{31}-1$ PRBS NRZ data. The composite signal was then applied to a RSOA, seeded by $\lambda_u$, the remotely delivered uplink optical carrier. RSOA directly superimposes the uplink traffic onto the optical carrier and broadcast the modulated signal in the uplink direction via the SC. For multipoint-to-multipoint transmissions enabling inter-communication among the customers of the neighboring H-BSs, the broadcasted uplink signal from one of the input ports of the SC is transmitted through another 2.2 km distribution SMF to a PD considered to be located in a neighboring H-BS. The PD and data recovery circuit is comprised of a 3 dB electrical splitter, one 750 MHz LPF, one 1 GHz BPF with a 3 dB bandwidth of 300 MHz and required signal conditioning devices.

Fig. 4 shows the RF spectra of the transmitted signals in the upstream direction from a H-BS. It contains of the 750 Mb/s baseband Ethernet data and the 155 Mb/s IF data on RF carrier at 1 GHz. The baseband data was band limited using a LPF while the IF data was band limited using a BPF to avoid the electrical crosstalk between these signals. The measured BER curves for all the signals are shown in Fig. 5. The BER curves for the 2.5 Gb/s downstream data confirm that the insertion of 10 km SMF and the addition of uplink...
carrier cause power penalties of 0.5 dB and 1 dB respectively. The measured BER curves for the redirected uplink signals (baseband and IF signals) exhibit negligible power penalties of less than 0.5 dB for 2.2 km SMF transmission and in the presence of downstream channel $\lambda_D$. For the point-to-multipoint transmission, the uplink signal can be routed back to the CO and can be detected by using suitable PD and data recovery circuit.

One of the issues considered for the use of the RSOA for the transmissions of baseband data in a PON is the burst mode operation of the RSOA as the baseband data transmission from the customers to the CO is usually based on time division multiple access protocol. Fig. 6 shows the observed traces from the RSOA output and it was found that RSOA turn-on and turn-off times are lower than 40 ns, which is lower than the required laser turn-on time of 512 ns specified in the IEEE standard 802.3. Fig. 6(b) shows that the first few bits of the 1.25 Gb/s data signals can be recovered successfully without any distortion.
## Table 1: The chosen parameters for the power budget analysis for a PON with varying splits of the SC.

Table 1 shows the parameters for a PON with varying splits of the SC. These parameters were not measured from the experiment, however they present realistic values of the network. It is considered that 10 km feeder fiber and 2 km distribution fiber are installed in the PON. To obtain a receiver sensitivity of -25 dBm or better for the 750 Mb/s baseband data, the seeding optical power into the RSOA needs to be higher than -23 dBm. The seeding optical power of -23 dBm into the RSOA gives a small signal gain of 25 dB. As it can be seen from Table 1, power margins of 4.5 dB and 1.5 dB can be obtained for the 750 Mb/s baseband data for the SC splits of 32, and 64 respectively. To obtain a seeding optical power of -23 dBm into the RSOA, approximately 1.5 dBm optical launch power is required at the CO for a PON with 32 splits.

### 3. Hybrid Base Station Scheme using VCSEL

The performance of the H-BS scheme using RSOA is limited by the narrow modulation bandwidth of the RSOA and selection of the optical LO from a coarse-wavelength (at least 20 nm apart from the downlink for the use of low cost realization of CWDM couplers). Also that scheme was relatively expensive, as it uses an expensive RSOA and an optical LO source for each H-BS. If the baseband Ethernet signals and the IF data signals are redirected to the CO to provide a communication channel between the H-BSs and the CO, then a separate feeder fiber may well be required to prevent the backscattering that limits the performance of the upstream signals. This setup might increase the cost of the network deployment. This has prompted us to investigate other optical sources that could potentially be used at the H-BSs without trading the complexity and cost. In that regard, it was found that single mode VCSELs can be used to directly modulate high frequency RF signals without any external modulators and they are relatively inexpensive compared to RSOAs and therefore provide a much more feasible solution for the use at the H-BSs.

The H-BS architecture that uses the VCSEL is similar to that of shown in Fig. 2. If the operating wavelength of the VCSEL is assigned to be far away from the downstream wavelength channel, a CWDM coupler can be sued...
at the H-BSs. On the other hand, if they are close to each other, an optical circulator can be used for the separation of these channels.

2.1 Experimental Demonstration

![Experimental setup for the demonstration of the H-BS scheme using VCSEL.](image)

Fig. 7: Experimental setup for the demonstration of the H-BS scheme using VCSEL.

Fig. 7 shows the experimental setup that demonstrates the capabilities of the proposed scheme. In the uplink direction, a 2.5 GHz BPSK RF signal, which was generated by mixing an LO signal of 2.5 GHz with a 155 Mb/s $2^{31}-1$ PRBS NRZ data, was electrically combined with a 1.25 Gb/s baseband signal of $2^{31}-1$ PRBS NRZ data. Before combing, the performance of the combined signal was duly optimized by managing and controlling the intensities as well as the harmonic components of each of the signal by using suitable electric filters and RF amplifiers.

The RF spectra of the combined signal can be seen in Fig. 8. The composite signal was then applied to a VCSEL via a bias-T. The remaining port of the bias-T was used to inject the drive current to the VCSEL. The VCSEL used in the demonstration was capable of handling a drive current of up to 15 mA offering a tunable emission bandwidth of 4 nm (1548 to 1552 nm). This specific demonstration has used a 9.3 mA drive current, which resulted in the directly modulated 1551 nm optical signal with an intensity of approximately 0 dBm. The directly modulated signal was then passed through a 3 port...
optical circulator and 3 km distribution SMF to the RAN where it is broadcasted via a 4 x 4 SC. The SC is connected with the CO and another H-BS (as described in Fig. 2) via a 10 km feeder and a 5.6 km distribution SMF respectively. To see the performance in point-to-multipoint communication, the broadcasted signal was then detected and both Ethernet and RF data was recovered in the CO using suitable PD and data recovery circuit. Shown in Fig. 7, the PD and data recovery circuit is comprised of a 3 dB electrical splitter, one 1.25 GHz low-pass filter (LPF), one 2.5 GHz band-pass filter (BPF) with a 3 dB bandwidth of 200 MHz and required signal conditioning devices. Similar to the point-to-multipoint communication, for multipoint-to-multipoint transmissions enabling inter-communication among the customers of the neighboring H-BSs, the broadcasted signal was also detected and both Ethernet and RF data was recovered in a neighbouring H-BS after the 5.6 km distribution SMF. The observed RF spectrum of the received signals is shown in Fig. 9. As shown in the BER curves in Fig. 10, error free data recovery confirm the functionality of the proposed scheme enabling the integration of baseband and RF signals. Regarding the scalability and link budget of the proposed scheme, VCSEL is capable of generating modulated signals with an intensity of approximately 0 dBm. Therefore, sufficient power margin is available.

Fig. 9: Observed RF spectra of the received upstream signals.

Fig. 10: Measured BER for all the signals.
4. Hybrid Base Station Scheme using E-CDMA

In the previous schemes, the traffic between the H-BSs is broadcast within the allocated timeslot. However, there exists a security problem whereby some of the H-BSs. Secure transmission of inter-H-BS traffic can be performed using encryption schemes. Since encryption is inherently a randomisation process, several encryption schemes could yield suboptimal results. The problem of generating random unpredictable encryption keys is one that is always overlooked. The use of secure tokens that emit cryptographically secure streams and noisy diodes that oscillate with unpredictable patterns have been used for encryption key generations. However, these encryption key generation schemes add complexity to the operation of the network. In this section, a physical layer security for the transmission of the LAN traffic is provided using electronic code division multiple access (E-CDMA). Improving the security of the transmitted signals at both higher layer and physical layer can lead to much improved performance of the network. In our proposal, the data to be transmitted amongst the H-BSs is electronically coded to generate an E-CDMA signal for the transmission to the selected H-BSs in the network. The H-BSs that have the knowledge of the E-CDMA spreading code, which was used for the encoding of the inter-H-BS traffic, can decode the data.

The scheme to illustrate the E-CDMA based data transmission is same as shown in Fig. 2. The upstream signals consist of the baseband data to CO and E-CDMA data that is modulated on an RF carrier to other H-BSs. At each H-BS, the looped back signals are detected and the upconverted RF E-CDMA data is electrically separated from the upstream baseband data using an electrical BPF. Then, the RF E-CDMA data is down-converted to baseband frequencies using a phase locked loop containing a voltage controlled oscillator (VCO) and using appropriate E-CDMA spreading code, the data is decoded. The upstream baseband data to the CO and the RF E-CDMA data are transmitted simultaneously in the same timeslot.

4.1 Experimental demonstration

The experimental setup to demonstrate the feasibility of this secure E-CDMA data transmission scheme is shown in Fig. 11. The downstream signal of $2^{31}-1$ PRBS NRZ data at 2.5 Gb/s was modulated onto $\lambda_d = 1550.148$ nm and transmitted to the H-BSs through a 10 km SMF, a $4 \times 4$ SC and a 2.2 km distribution fiber. For the upstream transmission, $2^{23}-1$ PRBS NRZ data at 10 Mb/s was electronically multiplexed with 16-bit, 160 Mb/s bipolar Walsh code 1 using a RF mixer and the resulting E-CDMA signal was modulated onto a 2.5 GHz RF carrier to generate the upconverted RF E-CDMA data, which was then electrically combined with 1.25 Gb/s $2^{31}-1$ PRBS NRZ data using a RF combiner. Fig. 12 shows the measured oscilloscope traces of the 160 Mb/s bipolar Walsh code, 10 Mb/s LAN data, and the resulting E-CDMA signal respectively. The E-CDMA signal shows that there is a phase change at the transition between ‘1s’ and ‘0s’ of the data. To avoid crosstalk between the combined baseband and RF signals, the RF E-CDMA data was bandlimited using a BPF with a centre frequency of 2.5 GHz and bandwidth of 300 MHz before the combination. Similarly, 1.25 Gb/s upstream

Fig. 12: Observed oscilloscope traces showing 160 Mb/s spreading code, 10 Mb/s data and the E-CDMA signal.
baseband data was band limited using a 1244 Mb/s LPF before the combination with the upconverted RF E-CDMA data.

Fig. 11: Experimental setup to demonstrate the secure transport scheme using E-CDMA signals on an RF subcarrier.

Fig. 13 shows the observed RF spectra at the upstream transmitter showing the 1.25 Gb/s upstream baseband and the 10 Mb/s E-CDMA data on 2.5 GHz RF carrier. Thereafter, the composite signals were modulated onto $\lambda_u = 1549.076$ nm using a MZM and transmitted in the upstream direction. The upstream signals were split in the SC whereby one portion was transmitted through the 10 km feeder fiber to the CO, while the other is redirected back to the ONUs through the second distribution fiber. The redirected signals were received at the RF E-CDMA data receiver. The detection of the upstream and downstream baseband signals was performed using 2.5 Gb/s p-i-n receivers, while the RF LAN data was detected using the 2.5 Gb/s APD receiver. For the recovery of 10 Mb/s data, the detected signals were fed
through a BPF centred at 2.5 GHz with a bandwidth of 300 MHz and the E-CDMA signal was down converted to baseband frequencies using the PLL based on a costas loop. For the decoding of the desired E-CDMA signal, appropriate electrical delay was employed to synchronise the local E-CDMA code with the incoming E-CDMA signals and 10 Mb/s data was recovered. As shown in Fig. 14, the optical spectra observed at the input of the downstream data receiver at H-BS and the upstream baseband data receiver at the CO show low levels of crosstalk signals which is due to the back scattered light in the fiber. The crosstalk levels in the upstream data and downstream data receivers were -30 dB and -28 dB respectively. These crosstalk levels were not expected to induce any power penalty for the recovered 2.5 Gb/s downstream data and 1.25 Gb/s upstream baseband data as can be confirmed in the BER curves. The crosstalk levels can further be suppressed using CWDM filters and choosing the upstream and downstream wavelength channels appropriately.

**Fig. 14:** Observed optical spectra at the upstream baseband data and downstream data receivers showing the suppression of the backscattered light.

**Fig. 15:** Measured BER for all the signals.
Fig. 15 shows the measured BER curves for all signals. For the 10 Mb/s data, a penalty of 0.2 dB was observed compared to B-B measurements when the RF E-CDMA signals were transmitted through the transmission link. An additional penalty of 1.2 dB was observed when 1.25 Gb/s upstream baseband data was included. This penalty can be attributed to the interchannel interference (ICI) crosstalk from the 1.25 Gb/s upstream baseband data. This crosstalk was induced by the non-optimum operating points in the MZM leading to nonlinear distortion of the RF E-CDMA data. In the presence of the downstream signals, the penalty was further increased by 0.2 dB. The BER curves for the 1.25 Gb/s upstream baseband data show a penalty of less than 0.3 dB compared to B-B measurements. No significant penalty was observed for the 2.5 Gb/s downstream data in the presence of other signals.

4.2 Power budget

Table 2 shows the measured experimental parameters for all signals showing the values of the transmitted power of all signals, the sensitivity and passive loss values of the components. As the number of H-BSs increases in the PON, the loss in the network increases due to the splitting loss of the SC and therefore limiting the transmission bit rates of the downstream data, upstream baseband data and upconverted RF E-CDMA data and the transmission distance.

<table>
<thead>
<tr>
<th></th>
<th>2.5 Gb/s downstream data</th>
<th>1.25 Gb/s upstream baseband data</th>
<th>155 Mb/s RF E-CDMA data</th>
</tr>
</thead>
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<tr>
<td>Transmitted Power</td>
<td>-7.86</td>
<td>-4.5</td>
<td>-4.5</td>
</tr>
<tr>
<td>WDM coupler loss @ CO</td>
<td>0.75</td>
<td>0.75</td>
<td>---</td>
</tr>
<tr>
<td>10 km feeder fiber loss</td>
<td>2.61</td>
<td>2.61</td>
<td>---</td>
</tr>
<tr>
<td>2.2 km distribution fiber loss</td>
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<td>0.69</td>
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</tr>
<tr>
<td>WDM coupler loss @ ONU</td>
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<td>0.75</td>
<td>0.75</td>
</tr>
<tr>
<td>Connectors / splices loss</td>
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<tr>
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<tr>
<td>Ageing and safety margin</td>
<td>3</td>
<td>3</td>
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</tbody>
</table>

Table 2: Measured experimental parameters for the transmission of all three signals.

This section investigates the scalability of the network as the number of splits in the SC is increased. For the transmission bit rates of the signals shown in Table 2, the power loss in all three signals result in an upper limit on the number of ONUs, $N$, that can be supported for given optical source powers and receiver sensitivities.

The insertion loss of the SC can be given as [9]

$$SC \text{ Loss} = 10 \log(2(N - 1))$$
Fig. 16 shows the calculated power margin for all signals as a function of the number of splits in the SC. As expected, the results show that as the number of splits in the SC increases, the power margin decreases for all signals due to increasing SC insertion loss from the increase in the number of splits. The power margin for the E-CDMA data is higher compared to that of the other data streams and it is because of better sensitivity for the recovered E-CDMA data. It should be noted that the calculated power margins for the 2.5 Gb/s downstream data and 1.25 Gb/s upstream baseband data are not affected by the inclusion of the E-CDMA data. They were resulted due to the poor sensitivity of the p-i-n receivers and lower launch powers used in the experiment. The power margins for all signals can be increased using higher launch power and optical receivers with better sensitivity.

5. Conclusions

We have proposed and demonstrated a hybrid base station scheme for the integration of wireless and wireline access technologies. The proposed scheme is based on standard device technologies and is suitable for any optical access/metro networks, irrespective of topologies and architectures. Moreover, this scheme has the potential to establish multipoint-to-multipoint communication without sending the signal back to the CO. We have experimentally demonstrated this hybrid base station scheme using Reflective semiconductor optical amplifier, vertical cavity surface emitting laser and Electronic code division multiple access scheme. The error-free data recovery in all schemes confirms the functionality of the scheme without any noticeable power penalty.
6. 

References


