A Novel In-Building Small-Cell Backhaul Architecture for Cost-Efficient Multi-Operator Multi-Service Coexistence

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Abstract: We demonstrate a novel in-building small-cell backhaul architecture for multi-operator, multi-service coexistence with optical infrastructure sharing. In-building experiments confirm 6-12Mb/s layer-4 packet throughputs for users under mobile distributed antenna and static frequency re-use scenarios, respectively.

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1. Introduction

Traffic growth due to mass proliferation of smart mobile devices and 4G and beyond wireless technologies is motivating a 5-10-fold increase in wireless cell sites to support small cell deployments as well as future-proof fiber-optic backhaul of the bandwidth-demanding mobile traffic [1-3]. This is particularly important for in-building networks, given that much of smart device traffic arises from indoors users, such that a strong majority of new sites may require indoor locations. In previous work [4], a software-reconfigurable mobile backhaul architecture based on WDM-OFDMA-PON capable of addressing heterogeneous small-cell deployment scenarios and supporting multiple operators was demonstrated. However, in [4], experimental measurements that include the effects of wireless multipath propagation, particularly indoors, were not presented, and all cell site equipment required full signal processing capability. For emerging in-building small-cell systems, however, indoor multipath effects must be quantified. Moreover, there is strong cost and complexity incentive to separate the digital processing baseband units (BBUs) of cell-site transceivers, from the largely analog radio access units (RAUs), and move the BBUs to the “cloud” for centralized, cost-efficient signal processing. One of the primary goals of the cloud-based approach is to both increase coverage for mobile users in the form of distributed antenna systems (DAS), as well as to enable spatial re-use of spectrum and increase total system capacity in so-called fractional frequency reuse (FFR) scenarios. To enable flexible heterogeneous DAS vs. FFR deployments in a cloud radio access network (RAN) context, we have proposed a reconfigurable architecture using centralized off-the-shelf optical switches, whereas optical switching for flexible DAS coverage during train travel was demonstrated in [5]. In this paper, we exploit centralized optical switching to demonstrate multi-operator coexistence and infrastructure sharing for in-building small-cell backhaul, enabled by a novel optical receiver design that exploits low-cost coarse division multiplexing (CWDM) components for simultaneous detection of multiple wavelengths carrying multiple RF signals from different sources. Multi-service coexistence via deployment scenario reconfigurability (i.e. DAS vs. FFR) is also confirmed. Experimental measurements including both optical backhaul and indoor wireless propagation effects are presented, confirming 6-12Mb/s layer-4 packet throughputs under the DAS and FFR scenarios, respectively. The demonstrated approach is thus shown to provide a flexible, cost-effective solution for multi-operator multi-service coexistence in an indoor network, while maintaining reconfigurability and centralized “cloud” networking benefits.

2. Small-Cell Backhaul Architecture and Receiver Design Principle

Fig. 1 illustrates the in-building small-cell backhaul architecture for a dual-operator, dual-service example. At the...
BBU pool, where the centralized digital processing power is located, the baseband data traffic from core networks is processed and up-converted to radio frequency (RF) via base station (BS) units. Since different operators and/or wireless services occupy different RF spectral bands, \( f_1, f_2, \) and \( f_3 \) represent the RF carrier frequencies of signals from different BSs. Each downstream RF signal is then intensity modulated onto a different CWDM optical wavelength, \( \lambda_1, \lambda_2, \lambda_3 \), respectively, using integrated off-the-shelf transceivers (Tx/Rx in Fig. 1) that are commercially available for bi-directional transmission (intensity modulation and direct photodetection) with RF bandwidth up to 7GHz [6]. This RF range covers the most of the commercial wireless communication bands. 1\times4\hspace{1mm} optical splitters (OS) and 4\times1\hspace{1mm} CWDM multiplexers (MUX) are used at the BBU pool to split and multiplex the downlink and uplink signals, as shown in Fig. 1 for the example of 3 active OS/MUX ports. An off-the-shelf optical switch with built-in independent on-off sub-switches (32 in our experiment) is next used to establish reconfigurable fiber-optic connections between the centralized BS units and distributed RAUs. For example, in the DAS scenario, the same signal is distributed to all RAUs to extend coverage for mobile users, while in the FFR scenario, different signals are transmitted to different RAUs to exploit spectral reuse and increase total system capacity for static users. By thus properly configuring the optical on-off switches in Fig. 1, the signal from BS1 on \( f_1 \) and \( \lambda_1 \) (from Operator 1) can be distributed to all three RAUs, as in a DAS scenario. To simultaneously emulate FFR scheme with a spectral re-use factor of 2 for Operator 2, the optical switches can be configured to distribute the signal from BS2 on \( f_2 \) and \( \lambda_2 \) to RAU1 and RAU3, while the signal from BS3 on \( f_3 \) and \( \lambda_3 \) is distributed to RAU2 (Fig. 1). While the switching functionality can be realized in either the optical [5] or electrical domains [4], the optical approach is adopted here to enhance energy efficiency. After the optical switch, downstream signals are CWDM-multiplexed and delivered to several in-building RAUs via optical fiber links. As shown in Fig. 1, to realize multi-operator, multi-service coexistence and fiber infrastructure sharing, in the proposed architecture, multiple wavelengths carrying multiple RF signals from different operators are all detected simultaneously by a single photodetector (PD) at each RAU, yet without interference. This key receiver-side feature of the novel architecture can be analyzed with a dual-wavelength, dual-service example, as follows: the electrical field of the optical multiplexed signals can be represented as \( E(t) = \sum_1^{n} S_i(t) \exp(i\omega_{opt1} t) \), where \( S_1(t) \) and \( S_2(t) \) denote the RF signals carried on wavelengths \( \lambda_1 \) and \( \lambda_2 \) (angular frequencies \( \omega_{opt1} \) and \( \omega_{opt2} \), respectively). \( B \) is the DC bias needed for intensity modulation, and \( \gamma \) represents the optical modulation index. After fiber transmission to the RAU, the signals are directly detected by a single PD. The generated electrical current is then given by: 

\[
I(t) = |E(t)|^2 = \sum_1^{n} |S_i(t)|^2 = |B + \gamma S_1(t)|^2 + |B + \gamma S_2(t)|^2 + \sum_1^{n} |S_i(t)|^2 
\]

From (1), we observe that the transmitted RF signals can be recovered from the expansion of the first term, while the second term represents the crosstalk between the two RF signals, carried on a radio frequency that is determined by the CWDM channel spacing. By proper selection of CWDM wavelengths, this crosstalk term will fall beyond the electrical bandwidth of the receiver-side PD and can thus be ignored. Consequently, the proposed architecture can enable infrastructure sharing among multiple operators without interference. Following photodetection, the multiple RF signals on different carrier frequencies are transmitted wirelessly to mobile subscribers (MS), where RF carrier frequency selection is executed, enabling multi-service support. Finally, as shown in Fig. 1, upstream transmission on the same RF spectral bands is enabled by CWDM wavelengths \( \lambda_2 \) to \( \lambda_3 \) using the switching mechanism above.

3. Experimental Setup and Results

The experimental setup for validating the proposed multi-operator, multi-service small-cell backhaul architecture is shown in Fig. 2(a) for the case of two operators and a single RAU. Specifically, two commercial WiMAX BSs are first used to generate independent 10MHz radio signals centered on two different RF carriers \( f_1 = 2.59GHz, f_2 = \)...

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**Fig. 2 (a)** Experimental setup of optical infrastructure sharing between two operators; (b) measured downlink throughput for small-cell optical backhaul transmission only; and (c) downlink throughput after optical backhaul and single-hop wireless transmission.
2.61GHz). The measured electrical spectra at the BS outputs are shown in insets (i) and (ii). Following intensity modulation onto wavelengths \( \lambda_1 = 1550\text{nm} \) and \( \lambda_2 = 1570\text{nm} \), the double sideband optical signals are CWDM-multiplexed and transmitted over 100m of standard single mode fiber (SSMF), corresponding to an in-building small-cell backhaul scenario, and photodetected by a 3-GHz PD. The measured electrical spectrum following the PD is shown in inset (iii) of Fig. 2(a), confirming the removal of the unwanted interference term, as described in equation (1). Finally, following single-hop wireless transmission of 2—15m, the downlink throughput was measured by a network bandwidth testing tool iperf, which computes successfully recovered layer-4 packets per unit time under the User Datagram Protocol (UDP). For the transport-layer throughput measurements, commercial WiMAX BSs and laptops equipped with commercial WiMAX client cards were used. As shown by Fig. 2(b), for the optical backhaul only case, stable 12—13Mb/s downlink throughputs were observed, with only minimal performance degradation due to the coexistence of signals on \( f_2 \) and \( f_3 \). A similar trend was observed for the optical plus wireless transmission cases (Fig. 2(c)), where, due to wireless transmission loss, multipath, and shadowing effects, throughput decreased from 12Mb/s to just under 3Mb/s as wireless transmission distance was increased from 2m to 15m.

To next demonstrate a larger-scale multi-operator coexistence with flexible configurations enabling heterogeneous service scenarios, a larger-scale in-building small-cell backhaul testbed was set up as shown in Fig. 3(a). In this case, 4 WiMAX BSs were centralized at the BBU pool, while 3 RAUs were distributed in the building as shown on the floor plan of Fig. 3(a). As shown in Fig. 3(b), 1 WiMAX BS \( (f_1 = 2.57\text{GHz}) \) is used in the DAS configuration to serve 2 mobile users MS1 and MS2 along a moving path denoted by checkpoints L1—L7. The remaining WiMAX BSs are used in the FFR configuration \( (f_2 = 2.61\text{GHz}, f_3 = 2.59\text{GHz}; \text{reuse } f_3 \text{ for BS2 and BS4}) \), serving two static users (SS1 and SS2). Both DAS and FFR configurations were thus running simultaneously. The output RF signals of four BSs are carried on four CWDM wavelengths \( (\lambda_1, \lambda_2, \lambda_3, \lambda_4) = (1490\text{nm}, 1510\text{nm}, 1530\text{nm}, 1550\text{nm}) \), respectively, with 4dBm per-\( \lambda \) optical launch power. The measured downlink throughputs for the DAS and FFR scenarios are shown in Fig. 3(c) and (d), respectively. For Operator 1, since the DAS configuration is used, the mobile users experience no degradation in the steady 6Mb/s throughput while moving across three small cells (L1 to L7, and back), even at the cell edges, highlighting the key coverage benefits of DAS. For Operator 2, since FFR with a reuse coefficient of 2 was exploited for static users, the system throughput is doubled to 12Mb/s for each user, which demonstrates the capacity benefits of this scheme. Consequently, the new architecture enables both operators to simultaneously run different small-cell backhaul scenarios by sharing the in-building optical infrastructure, without interference.

4. Conclusions

We have experimentally demonstrated a novel in-building small-cell backhaul architecture for cost-efficient multi-operator, multi-service coexistence over a common optical infrastructure. In-building experiments using a novel approach for multi-signal reception have confirmed 6-12Mb/s throughputs with virtually no optical receiver-side interference. This architecture is thus shown to be promising for future small-cell optical backhaul systems.

References