Optical Network Architectures for Dynamic Reconfiguration of Full Duplex, Multi-wavelength, Radio-over-Fibre.

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In recent years there have been rapid advances in the techniques to generate and transport radio signals over optical fibre, however very little has been done to date to develop the concept of a full duplex, multi-wavelength, radio-over-fibre network architecture that intrinsically supports and facilitates the dynamic reconfiguration of the wireless network. Recently the development of suitable architectures has received attention, with some approaches concentrating on the fibre radio link layer [1] and others focusing on the optical WDM layer [2,3]. Here we present for the first time an approach which aims to vertically integrate the cellular radio layer, the fibre radio layer, the optical networking layer and the physical layer to achieve a network architecture that enables the dynamic reconfiguration of the cellular wireless network layer.

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1. Introduction

The implementation of radio-over-fibre networks that allow simplified Radio Access Units (RAU) to be deployed that are connected by optical fibre has been widely researched in recent years and is beginning to attract increased commercial attention. The main principle of such networks is to move the majority of the complexsignal processing involved in wireless transmission away from the base-station to the central office. The 'ready to air' signal is then transported to/from the antenna site via optical fibre. The majority of research has focused on the optical techniques for the transport of radio frequencies from signals in the UHF band to signals up to and beyond 60GHz [1,2]. Commercially available systems have generally provided mobile services (GSM and UMTS, with WLAN starting to be offered) for either areas of very high capacity [3] or in areas where coverage is weak, for example in buildings [4]. Until recently virtually all systems considered point to point links for each antenna and therefore only really constitute distributed antenna system.

Consideration has now started to be given to the design of optical delivery networks that provide the ability to dynamically reconfigure the wireless network. This would enable the real-time optimisation of the coverage/capacity compromise by making use of an optically supported wireless network. This takes advantage of the fact that now all the base-station equipment is co-located in the central office reorganisation of resources is possible. Some initial investigations in possible network configurations have been made; for example switching at the data level has been considered [5] as well as the switching of RF sub-carriers [6]. More recently ring architectures have been considered with fixed add-drop multiplexers [7]. However, very little work has been undertaken that considers the interaction of the radio and optical layers to form a transparent optical layer supporting reconfigurable radio access.

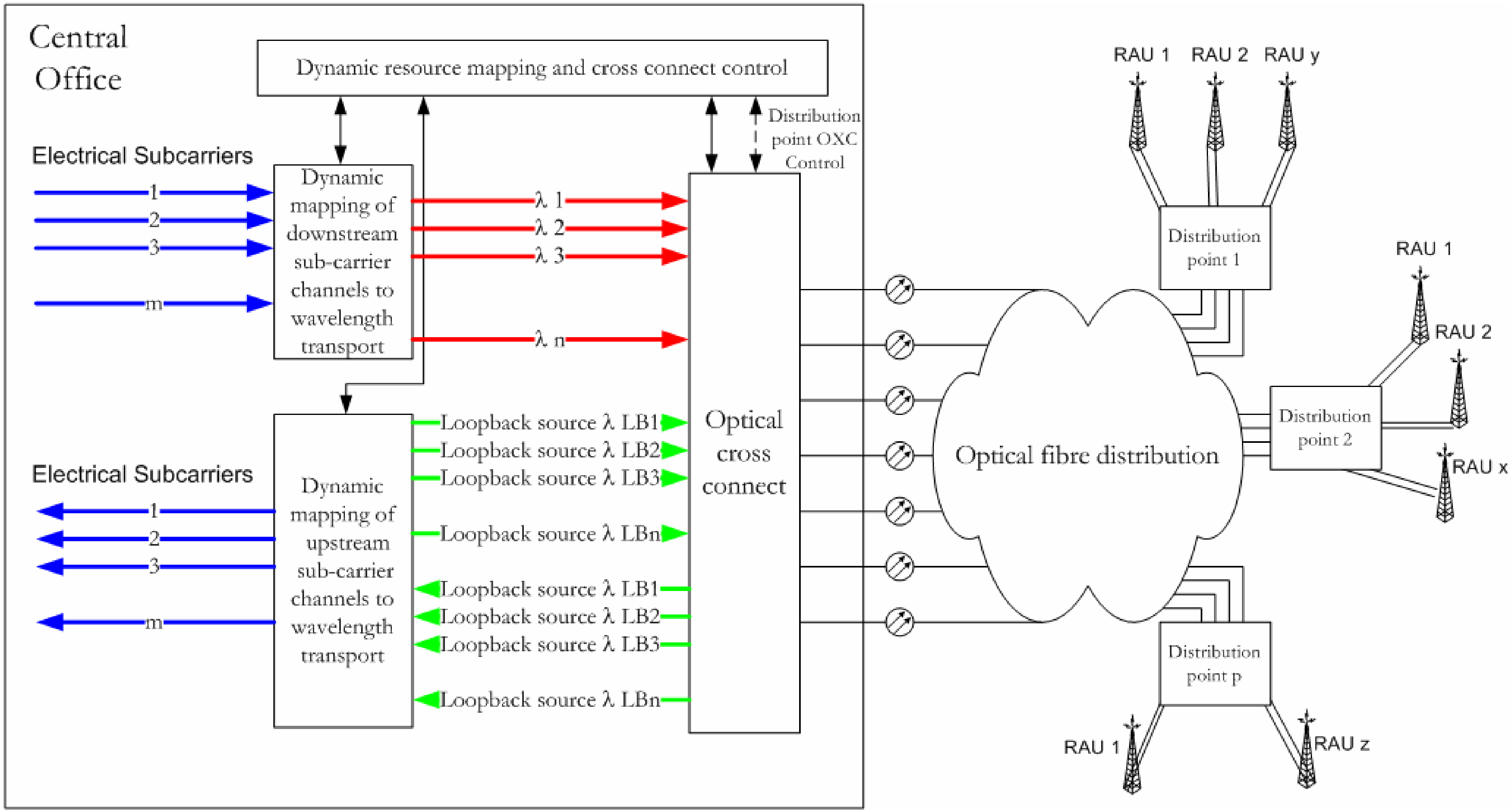

Figure 1: Wireless capacity reconfiguration on a WDM optical network support radio services.

In this paper we consider the technical implication of such a network and in addition consider how this wireless backhaul service may be provided as an overlay on a Passive Optical Network (PON) and thereby reuse much of the existing fibre infrastructure. The main advantage that dynamic reconfiguration provides is that finite head-end resources may be deployed under dynamic network control, to where they are temporally most needed, resulting in their more efficient use. In a wireless network the radio capacity per user may be increased by:-

(i) Overlaying cells - This is implemented by increasing the number of RF sub-carriers transmitted from a RAU. Increasing the number of RF sub-carriers within a cell increases the capacity available to the users within the cell coverage.

(ii) Decreasing the cell size – This may be effectively carried out by sectoring the cell, varying the transmitted power from the RAU or adopting a higher order modulation scheme. Decreasing the cell coverage area has the effect of reducing the number of users within the cell coverage area. Therefore, even if the cell capacity available has been kept constant, due to the decreased number of users within the cell coverage area, the capacity per user will be increased. Conversely, the cell capacity per user may be decreased by removing the overlay cells or by increasing the cell coverage area.

The design of a dynamically reconfigurable micro/pico-cellular wireless overlay network involves a cost/complexity compromise. On the one hand, using the traditional base-station approach requires the equipping of all the wireless nodes for the highest capacity ever needed which results in the inefficient use of resources. While the ability to dynamically reconfigure the network increases the network complexity. Similarly within the optical access network layer traditional power splitting PONs achieve coverage efficiently whereas WDM PONs allow an extra level of reconfiguration as wavelength can be used as an additional routing dimension. In such a network RAUs may be addressed by wavelength either by static or dynamic routing. Consequently, the implementation within an optical access network distribution point of the functionality to change the logical structure of the optical access network dynamically would be a valuable asset. This would enable the structure of the optical distribution network to be changed between that of a power splitting PON and that of a wavelength routed PON. Equipping the optical distribution point with an optical cross connect functionality would enable the dynamic reconfiguration of the star network connecting the different RAUs.

Further adding “drop and continue” functionality to the optical cross-connect (installed at the optical distribution point) would enable the dynamic reconfiguration of the ‘last drop’ star network in to a logical power splitting PON. Therefore, it would be possible to have a mixed logical configuration of the star network coming out of a distribution point with a combination of a power splitting PON facilitating wavelength sharing with that of a WDM PON facilitating the direct allocation of resources to an RAU.

Figure 1 illustrates a radio over fibre (RoF) architecture that inherently supports the dynamic reconfiguration of the wireless network. At the central office head-end a finite number m of downstream electrical sub-carrier channels are dynamically mapped to a finite number n of downstream wavelength channels. The optical cross-connect at the central office then maps the individual wavelengths to the optical fibre strand feeding the distribution point, feeding the destination RAU. At the distribution point another optical cross-connect feeds the wavelength on to the required RAU (or group of RAUs if the wavelength is a shared one – this would require a logical power splitting PON configuration).

The head-end also contains a number of wavelength sources serving as looped back sources for the upstream channels. These are again dynamically mapped to the RAUs as required, modulated at the RAUs and looped back to the central office where the electrical sub-carriers are received. The network is controlled by a dynamic, resource mapping and cross-connect control function. Such a function controls the overlay and operation of the optical and wireless layers by controlling and optimising the mapping of the wavelengths and the electrical sub-carriers to the individual RAUs. Its operation is wholly based on a detailed knowledge of the properties of all the network layers involved, culminating in the tight vertical integration of the Sub-carrier→Wavelength→RAU mapping schemes.

The next sections analyse the various Sub-carrier→Wavelength→RAU mapping schemes, and identify the network functionality necessary for their implementation together with their relative advantages and disadvantages. In section 2 we consider the Wavelength→RAU mapping schemes that various optical network implementations can provide. This is followed in section 3 by the Sub-carrier→Wavelength→RAU mapping schemes. We demonstrate the level of vertical integration required to offer a fully dynamically reconfigurable network.

2. Wavelength® RAU mapping schemes

The wavelength→RAU mapping scheme enables the bidirectional visibility of the various RAUs from the head-end, and it is very tightly coupled to the functionality present in the optical access layer.

Various mapping schemes are possible, ranging from simple wavelength sharing schemes to complex dynamically reconfigurable schemes. Various Wavelength→RAU mapping schemes are outlined below, where the network functionality required for their operation together with their relative advantages and disadvantages are discussed. Here, we have only considered schemes that map a single wavelength per RAU. It is possible to design schemes that map multiple wavelengths to an RAU, however these require that careful consideration is given to optical filtering requirements, additive crosstalk, photodiode saturation and RAU complexity. The basic mapping schemes considered here are the fundamental ones, although it is possible to create several hybrids from these basic schemes.

2.1 - 1:*n* Static Wavelength mapping scheme

The implementation of a 1:*n* static wavelength mapping scheme is illustrated in figure 2 and may be achieved by mapping the downstream RAU wavelength to a power splitting PON (such as a G.983 PON [4]) interconnecting *n* RAUs. This enables the wavelength to be effectively shared between the *n* RAUs. No additional functionality is required in the distribution network other than that required by a G.983 PON with services delivered within the enhancement band. At the Optical Network Unit (ONU) the G.983 downstream wavelength and the RAU wavelength are separated using a wavelength division multiplexer and delivered to the ONU and the RAU respectively. Unless simulcast operation is required, electrical filters will be needed at the RAU to select the appropriate sub-carrier multiplexed (SCM) channel. The technical feasibility of transporting data and radio signals has been demonstrated for a number of data-rates and radio frequencies [5,6].

This architecture has the advantage of allowing a single wavelength to be shared amongst *n* RAUs to provide an efficient use of head-end optical and sub-carrier resources while requiring minimal changes to the PON infrastructure. In particular, if the PON is designed to use the enhancement bands, optical filtering in the ONU will already be present. However, due to the broadcast nature of the RoF signal careful optical and electrical frequency planning must be carried out as there is virtually no reconfigurability. The main issue that will be encountered is in providing the upstream radio channel. As a single wavelength is shared between a number of RAUs, a media access scheme must be implemented that is compatible with the radio interface; in most cases this is very difficult to do as it conflicts with the media access of the radio channel. There is an additional layer of complexity involved over traditional baseband PONs due to the dual MAC layers; one being required to allow multiple access the optical fibre and the other inherent in the radio protocol to allow access to the radio spectrum Therefore this technique is most appropriate where broadcast services are to be delivered.

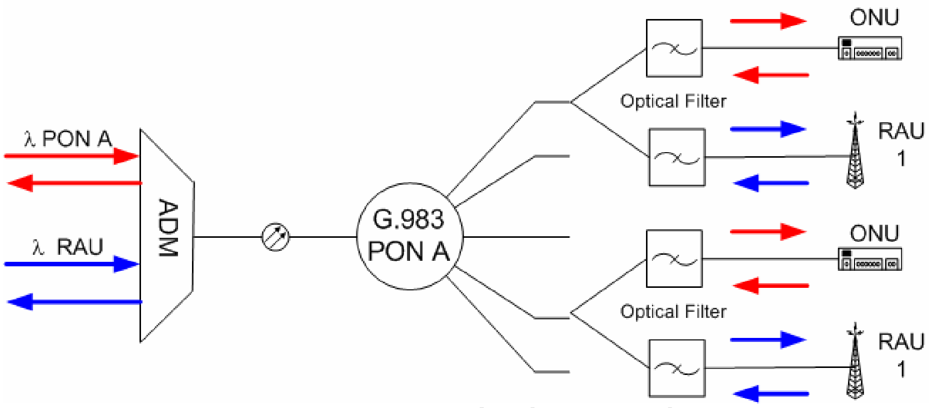

Figure 2: 1:*n* Static wavelength mapping scheme

2.2 - 1:1 Static Wavelength mapping scheme

As an enhancement a 1:1 static wavelength mapping scheme may be implemented, figure 3, by incorporating a static wavelength routing device such as an arrayed waveguide grating (AWG) in distribution point. This offers an increased level of reconfigurability by allowing signals to be flexibly assigned to RAUs based on their allocation of a particular wavelength. As only the wavelength specified will reach the RAU electrical filtering of sub-carriers is not longer required. An RF switching matrix [6] can be used to allocate the sub-carriers to the correct laser which addresses the RAU, and allows the operator the flexibility to provide multiple sub-carriers to an RAU to specifically increase its capacity. This increased flexibility comes at a price, as this implementation makes inefficient use of head-end optical resources requiring an individual laser for each station. However, a distinct advantage is that only passive components are required in the distribution section of the network, therefore maintaining the *passive* optical network.

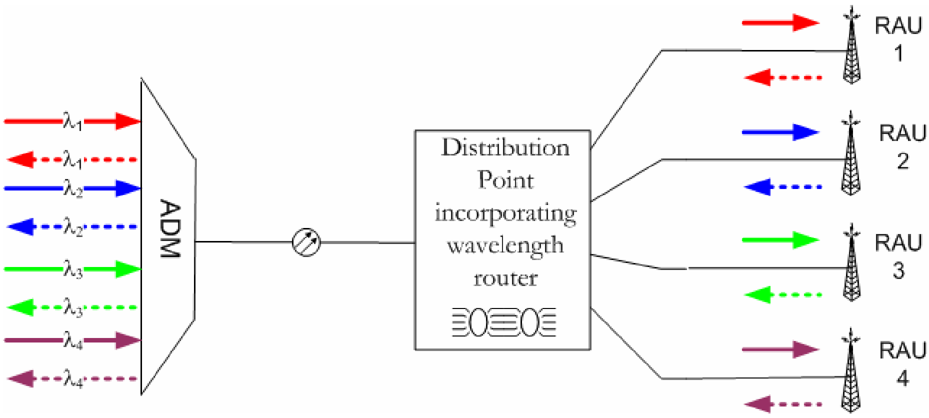

Figure 3: 1:1 Static wavelength mapping scheme

2.3 - 1:1 Dynamic Wavelength mapping scheme

To enhance the flexibility further additional control of the optical path is required. A 1:1 dynamic wavelength mapping scheme, illustrated in figure 4, makes use of an optical cross-connect architecture at the head-end to map wavelengths to individual access network fibres. These are then addressed to RAUs using the wavelength routing discussed in section 2.2. This architecture effectively joins a number of 1:1 Static Wavelength routed access networks together to afford head-end resource savings through the dynamic allocation of wavelengths to each network. However, these savings can only be realised if certain parts of the network require no coverage at a particular point in time.

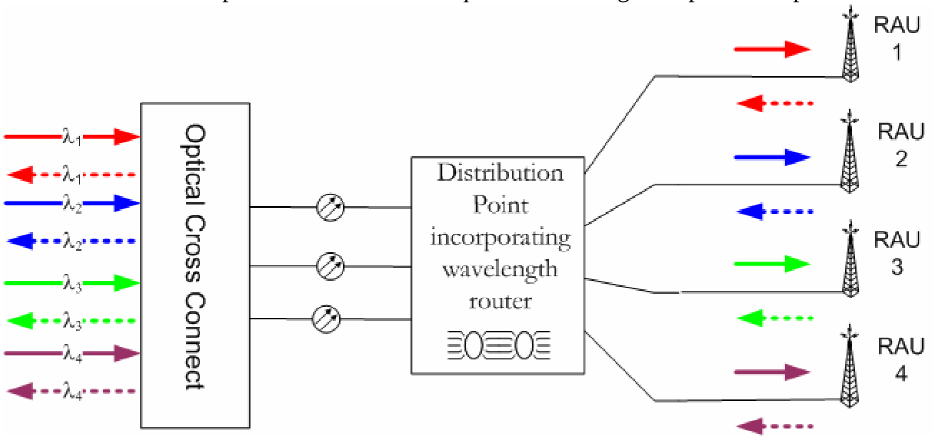

Figure 4: 1:1 Dynamic wavelength mapping scheme

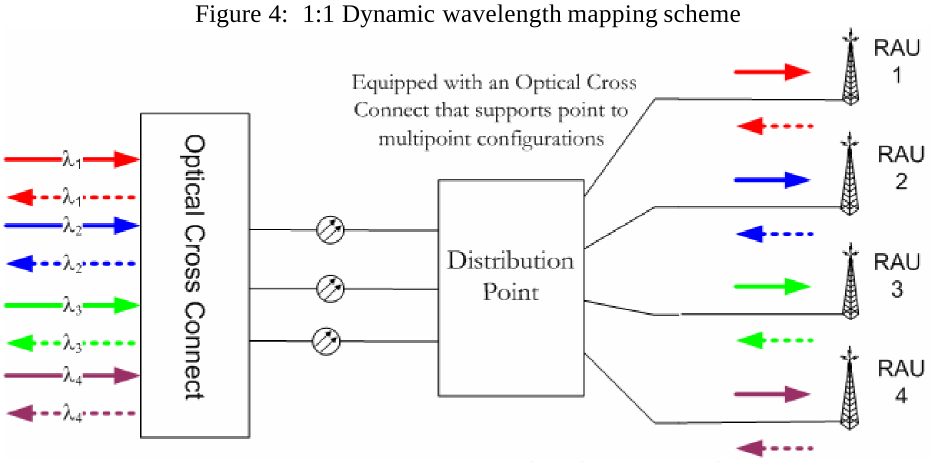

Figure 5: 1:(1 or *n*) Dynamic wavelength mapping scheme

2.4 - 1:(1 or *n*) Dynamic Wavelength mapping scheme

As discussed above the 1:1 dynamic mapping scheme has serious drawbacks. This can be solved by implementing a 1:N scheme as shown in figure 5. This required an optical cross-connect in both the head-end and the distribution point, with this second cross-connect equipped with the ability to route an input wavelength to more than one output. This allows flexibility to switch between point to point and point to multi-point configurations so that it is able to dynamically reconfigure from a star RAU last drop network to a logical power splitting or WDM PON. This architecture supports full reconfigurability and allows all RAUs to provide a mix from high capacity to basic service simultaneously. However, the requirement for complex optical switching equipment to be deployed in the field is not particularly attractive in many operators. Also complex dynamic mapping and resource control is needed to manage the network to ensure that blocking does not occur. This arises due to the two points of cross connection.

It is therefore likely that sub-optimum configurations will often have to be implemented unless accurate prediction of likely future configurations is available.

3. Sub-carrier ®Wavelength® RAU mapping scheme

The Sub-carrier→Wavelength→RAU mapping scheme is responsible for mapping the electrical sub-carriers to the appropriate wavelength which addresses the target RAU. Multiple sub-carriers may be mapped to a single wavelength using sub-carrier multiplexing (SCM). SCM is carried out by summing the multiple radio sub-carriers using a power combiner and then using the composite signal to intensity-modulate the optical source. SCM provides a simple, transparent way to share the bandwidth of an optical wavelength channel.

The design of directly modulated laser systems employing SCM has been thoroughly studied in the literature [7,8] because of their important role in CATV networks, and the interplay of laser relative intensity noise, shot noise, thermal noise, intermodulation distortion, modulation index, system budget and laser clipping on the number of electrical sub-carriers that can be multiplexed on an optical carrier is well known. It is also well known that intermodulation distortion causes the performance to vary among the different electrical sub-carrier channels within the band leading to the development of optimized electrical sub-carrier frequency plans [9].

Several Sub-carrier→Wavelength→RAU mapping schemes are possible ranging from simple sub-carrier sharing schemes to complex dynamically reconfigurable schemes. In this section we focus on the Sub-carrier→Wavelength mapping schemes since the range of Wavelengt →RAU mapping schemes has been discussed in the previous section. Various Sub-carrier→Wavelength mapping schemes are outlined below, where the network functionality required for their operation together with their relative advantages and disadvantages are discussed.

3.1 - Simulcast operation

In a simulcast operation a set of RAUs are grouped together as a single cell, also called a supercell. On the downlink all the RAUs within the group receive from the central office and consequently transmit the same radio signal (albeit with some relative propagation delays), while on the uplink the different RAUs receive and forward the same RF signal to the head-end. The RAUs therefore resemble a distributed antenna system or space diversity system. Recently simulcast operation has been the subject of increased attention due to its application in DVB-T transmission. This mapping scheme is illustrated in figure 6.

This mapping scheme is ideal when there is a requirement to cover a number of cells with a low capacity requirement. The supercell offers wide area coverage while conserving sub-carrier resources. The scheme reduces the need for handovers as the supercell become effectively a single cell as far as the wireless access protocol is concerned. It requires that the wireless protocol is capable of supporting this configuration. The implementation can take a number of forms; networks with a form of ad-hoc connect such as 802.11 are compatible as long as interference from the multiple transmissions does not significantly degrade the signal.

For more structured protocols such as GSM, a mechanism will need to be included that enables signals to be handed off from their original frequency to the new frequency that covers the supercell. A complication is the mechanism that is required to dynamically reconfigure the supercell as the usage increases. As individual signalling is no longer available from constituent cells, it is impossible to know which cell within the supercell would most benefit from being allocated a separate frequency. The easiest scheme to implement would require the complete break up and reformation of the supercell, however this removes some of the resource savings.

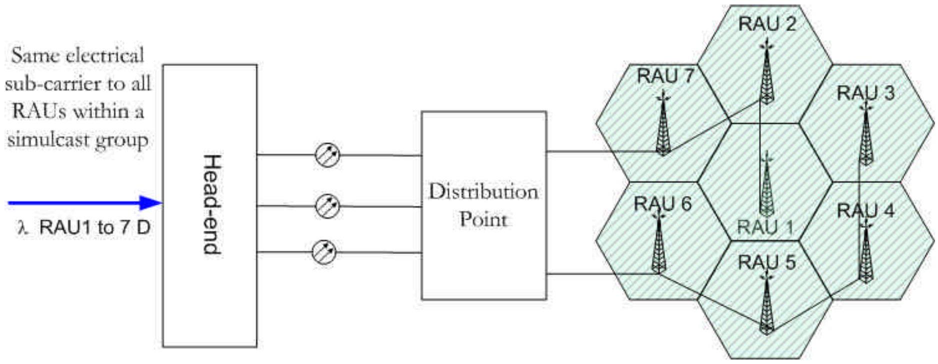

Figure 6: Simulcast electrical sub-carrier mapping scheme

3.2 - 1:1 Sub-carrier® RAU mapping

In a 1:1 electrical sub-carrier to RAU mapping scheme, a unique electrical sub-carrier per RAU scheme is adopted. This enables a basic coverage to be obtained, resulting in the traditional cellular frequency reuse cluster illustrated in figure 7. If capacity needs to be increased dynamically at an RAU, more sub-carriers may be temporarily mapped to this RAU until the maximum SCM capacity of the wavelength is reached. This produces a simple capacity reconfiguration scheme making use of an overlaid cell. It only requires simple mapping techniques and removes the requirement for electrical filtering (which in some instances needs to be tunable) at the RAU.

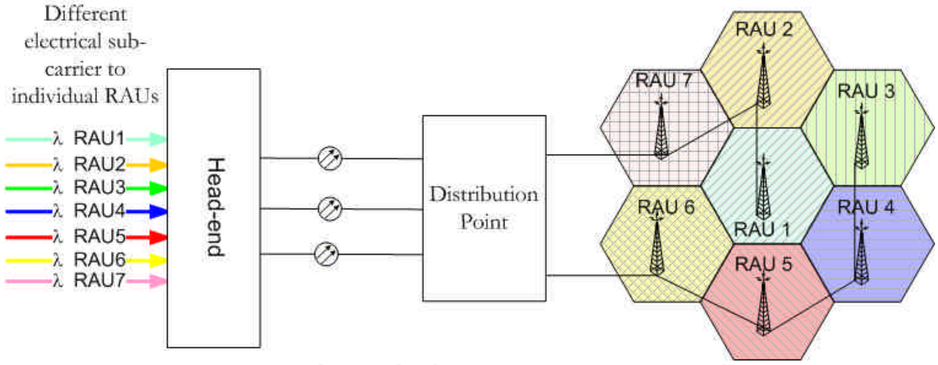

Figure 7: 1:1 electrical sub-carrier→RAU mapping scheme

However, in most instances where only a relatively small number of frequencies (sub-carriers) are available a very small frequency reuse scheme is required. The addition of sub-carriers to a RAU may also cause issues for components in the RF transmission chain. For example, even if wide band power amplifiers are used the addition of a new sub-carrier may cause a power penalty which will reduce the coverage area of the cell. Unless gain control is used this can lead to blind spots in the network.

3.3 - Hybrid simulcasting & 1:1 sub-carrier® RAU mapping scheme

In a hybrid simulcasting and 1:1 electrical sub-carrier to RAU mapping scheme, a mix between the two individual schemes may be adopted dynamically depending on the instantaneous traffic conditions in the network. Such a scheme enables a basic coverage to be maintained, while maximising the availability of resources to areas under congestion. This results in an optimum coverage – capacity compromise. Such a scheme merges very well with a network supporting 1:1 or 1:*n* dynamic wavelength mapping. An example of the resulting cellular overlay is illustrated in figure 8.

This scheme has the advantage of being able provide the full range of capacity, allowing basic coverage to be maintained, while maximising the availability of resources to areas experiencing congestion. Of course this advanced flexibility requires complex management in the network to provide dynamic mapping functions and resource control. Again when simulcast operation is used the same issues of how decisions are made regarding cell formation are present. If these design problems can be overcome then this scheme achieves optimum use of head-end resources, while also maximising the grade of service experienced by the mobile entity.

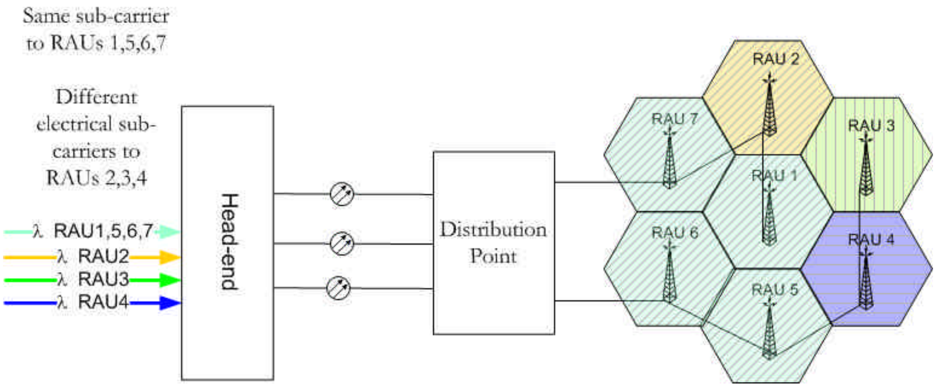

Figure 8: Hybrid simulcasting / 1:1 electrical sub-carrier→RAU mapping scheme

4. Conclusions

In this paper we have classified the various options available for the design of a full duplex, WDM overlay architecture that is capable of delivering radio-over-fibre services. It particular the optical networking requirements are shown to take advantage of the fibre plant installed to provide passive optical networking services. We have proposed various sub-carrier→wavelength→RAU mapping schemes and outlined their relative advantages and disadvantages.

Consequently it may be argued that prior to the widespread deployment of reconfigurable radio-over-fibre networks over a wide area the following important architectural issues must be resolved:

1) The need for a dull duplex, networked focused, approach to radio-over-fibre architecture definition and design;
2) The need for radio-over-fibre systems to coexist on the same fibre infrastructure with other systems or services; e.g. the development of suitable multi-wavelength operation schemes, an area where detailed analysis of the optical crosstalk effects present in such networks is key;
3) The need for WDM radio-over-fibre systems to inherently support and facilitate the flexible reconfiguration of the wireless network. This requires the design of a vertically and horizontally integrated network ensuring that future wireless networks and system have radio-over-fibre network capability.

Detailed schemes and protocols need to be devised to efficiently manage and control these highly reconfigurable networks. This management capability need to be vertically integrated across all layers to provide optimum performances, as it requires control of all levels of the network from the optical path, through the sub-carrier assignment up to the radio protocol.

Our aim has been to discuss the technical options that are available, and demonstrate the service and management improvements that may be obtained by their implementation. However, for operational or cost reasons, introduction of additional complexity in the distribution network may not be desirable. Careful planning will be required to balance the functionality increase possible with the implementation costs.

Much more research needs to be undertaken, both on an individual layer basis as well as on the vertical integration of the various layers comprising a WDM radio-over-fibre overlay. However, as this paper has described such an overlay has the potential to enable an optical access network to offer a quad-play of broadband services consisting of voice, data, video and mobile. This would enable the costs of a pervasive optical access network deployment to be shared over more services and operators, while integrating a level of functionality that is difficult to achieve using other non-integrated methods.

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