Hierarchical Wireless and Optical Access Networking: 
Convergence and Energy Efficiency

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ABSTRACT
Node consolidation and an all-passive (PON) infrastructure are important aspects to next-generation optical access (NGOA) networking. Wireless access is another important trend (WiFi, LTE/4G etc.) but requires active outside plant (base-stations). Once electrically-powered (e.g. via renewable energy) outside plant becomes a feature of an integrated NGOA architecture, the question of whether the NGOA network can be adapted and optimised still further (e.g. location of cognitive radio intelligence, vertical handover, locality, caching/content storage etc.) needs to be explored, as well as the additional energy-efficiency savings available with respect to optimising green radio technologies versus low-energy photonics. In this paper, we discuss the issues involved in the optimised design of a hierarchical and converged fixed-wireless access network, focussing on the handover possibilities associated with heterogeneous wireless technologies and the impact on the optimised design of an underlying fixed optical access infrastructure.

Keywords: Next-generation access networking, wireless networking, energy efficiency, network convergence, passive optical networking, green radio.

1. INTRODUCTION

Fixed-mobile convergence has been predicted as a long-term trend for many years, under the name of Edholm’s Law [1] – another one of the laws in the same ICT canon as Moore’s Law. Up to now convergence has been a slow process, with predictions on current trends suggesting that full convergence will only occur in the 2030 timeframe [1]. That said, it is also clear that the broadband access space is now finally undergoing radical change, with fibre-to-the-home (FTTH) being actively pursued by incumbent operators (telcos and cable operators) [2] as well as new-entrant competitors and municipal institutions, with per-user bandwidths of up to 1 Gb/s also expected to be offered over fixed-line infrastructures in the 2020 timeframe, i.e. as according to Nielson’s Law [3]. Another important development in the access context has been the emergence of WiFi-based femto-cell technology, particularly within the home (inside buildings) offering wireless final connectivity via home gateways or wireless access points [4]. The ever greater sophistication and potentiality of wireless devices (both for personal and machine-to-machine connectivities etc.) means that they are increasingly embedding themselves into our everyday lives, with full mobility becoming an ever more fundamental technology requirement.

In the context of Edholm’s Law, WiFi and 3G convergence has already occurred, with seamless transitioning between the two technologies and automatic vertical handover from WiFi hotspots to broader 3G coverage [5].

Figure 1: Fully-converged wireless-fixed access network, featuring a hierarchy of wireless cells: external macro-micro-pico cells and femto-cells for within-building access. Network intelligence and cognitive radio techniques can be exploited to offer additional access network energy-efficiency savings.
This aspect represents a fulfilment of two of the original three strands to Edholm’s Law, with 3G representing the mobile and WiFi representing the nomadic technologies. Convergence with the underlying fixed-line infrastructure is now beginning to be seriously considered [6], with specific projects now starting to actively consider architectural possibilities [7,8]. In the context of energy efficient (EE) networking, a fully converged mobile-fixed access network is also offering itself as an attractive opportunity to create an overall optimally “green” access technology solution, e.g. [9].

2. ISSUES IN CONVERGED WIRELESS-OPTICAL NETWORK DESIGN OPTIMISATION

Clear tensions between the topological optimisation of optical access networking architectures and wireless infrastructures are, however, obvious. For example, an important trend in next-generation optical access (NGOA) is node consolidation and the desire for passive optical infrastructure between optical network units (ONUs) and the central access node (CAN) [10]. On the one hand, base stations (BSs) require electrical powering (currently quite substantial, e.g. in the kW range [11], but likely to reduce significantly in the future, e.g. to 10’s of watts [12]), which is incompatible with the conventional PON (and frequently NGOA) philosophy of avoiding active outside plant. Naturally, there’s nothing to stop a base station being locally powered (e.g. by renewable energy sources [13]) and still terminated with a conventional ONU at the end of PON. However, once electrically-powered or active intermediate (outside) plant becomes a feature of an integrated NGOA architecture, it begs the question of whether the NGOA architecture should itself be adapted and optimised still further to take this into account (i.e. relax the requirement for no outside electrical equipment) For example, issues of locality and content storage (caching and content distribution) as well as the location of network intelligence (cognitive radio) closer to end-users tend to require active equipment at the periphery of the access network in order to achieve its greatest effectiveness in reducing overall use of network resources and a lower overall carbon footprint.

Another tension is the desire for node consolidation, which is seeing NGOA architectures being designed to allow central access nodes (CANS) to extend out to 20-40 km (passive) and even to 60 km and beyond (active, and 100-km long-reach (LR)-PONs etc. [10]) from end-users. For hybrid radio-optical access networks, this has practical implications for the wireless handover protocols, which place strict limits on the allowed latency of radio signals. For example, if a CAN (where the network management handling the handover protocol issues between BSs might be located) is connected by 100 km of optical fibre to the BSs, this means a 200 km roundtrip for the optical part of the signalling, which is associated with an additional minimum delay of at least 1 millisecond. As such, NGOA networks featuring active intermediate equipment closer to the BSs, e.g. as might be considered in an active optical network (AON), may have to be considered in future access network design. In this context, active equipment (especially, if based on intense processing electronics for network intelligence) is likely to be associated with additional electrical power requirements. This would appear to be incompatible with a greener, low-power access network. However, by co-locating such active equipment with wireless BSs, provided both technologies are sufficiently scaled (i.e. not representing a high-power network node, but rather a more local wireless access point) then their electrical energy requirements may be adequately provided for by a renewable power source (solar, wind, energy harvesting etc.) to allow carbon neutral operation. (We note, in passing that a full life-cycle analysis of the carbon footprint of such renewable energy technologies is, however, still an open issue.)

Analogue radio-over-fibre (RoF) techniques also offer interesting possibilities for reductions in both capital expenditure (CapEx) as well as simplification of active equipment at BSs. In this case, digital signals are digitally modulated onto an optical wavelength at the BS, and then transmitted as an analogue optical signal towards the central office (CO) or CAN. Any cognitive processing of the wireless signals can then be performed at the CO/CAN, offering potential economies of scale advantages. In addition, a simpler analogue RoF opto-electronic interface [14] at the BS requires lower power for operation, and therefore makes itself a still more appropriate technology candidate for powering by renewable energy sources.

3. HIERARCHICAL WIRELESS TOPOLOGY FOR MAXIMAL ENERGY EFFICIENCY

Although LTE (long-term evolution) is the successor technology to 3G in terms of bandwidth capability [15], considering its physical coverage footprint LTE can also be considered as a geographically intermediate wireless technology between 3G and WiFi. In this case LTE operates on a smaller (micro/pico-cell) size, compared to the macro-cell scale of 3G; but which is still considerably larger than the femto-cell sizes associated with WiFi. Here, we describe a converged access infrastructure featuring a hierarchy of different cell sizes, according to user densities, bandwidth requirements, and their own energy-efficiency (EE) considerations, ranging from macro -> micro -> pico -> femto cell sizes, as shown in Figure 1. Such a multi-level, hierarchical approach also offers additional opportunities for EE optimisation as well as flexibility in the design of NGOA topology. In the context of EE optimisation, green radio technologies such as MIMO adaptive antennas [16], power amplifiers [11] and beam-forming [17] can all be employed to minimise energy consumption within a radio access cell.
An additional degree of freedom therefore exists for minimising power consumption, such that base stations can be powered down (put into sleep, idle modes, discontinuous reception etc. [18]) and the traffic transferred to another BS which may overlap the same footprint coverage. The relative energy efficiencies between macro, micro, pico and femto cells are not as yet clear – EE depends on many factors (data bandwidth throughput, densities and no. of end users, cell size, as well as the relative maturity/age of the individual technologies employed etc.) However, assuming that certain BS configurations in a given usage context offer distinct EE advantages, it is clear that automatically performing a vertical hand-over of end-users from one type of base station to another BS offers an alternative means to minimising power consumption and globally optimising NGOA energy efficiency. Designing a NGOA topology to enable flexible BS cell sizes within a BS hierarchy (macro-micro-pico-femto) for optimised energy consumption and bandwidth throughput adds an additional level of complexity to NGOA architecture design, which is now the subject of ongoing research.

A hierarchy of varying cell sizes is also an issue when considering energy efficiency for high-velocity mobile users (i.e. within-vehicular broadband access.) Although local vertical handover protocols may provide fast transfer between different radio cells, it’s clear that rapid handover between a multiplicity of micro/pico cells is undesirable (and represents a potentially highly inefficient use of network resources) when an end-user is travelling at speed through a series of wireless access cells. In this case, a larger, macro-cellular structure offers a more efficient and slower rate of network handover. In this case, efficient handling of handover at the macro-cellular level is also best performed at the CO/CAN.

4. RESILIENCE AND PROTECTION CONSIDERATIONS

The use of an adaptive hierarchical topology of base stations also offers an alternative means for the provision of resilience and protection in the NGOA context. For example, although protection is envisaged between the CAN (or possibly CO) and aggregation/core parts of the network, relatively little is currently considered for the “last mile”, with dualling suggested up to the remote node (RN) part of a PON, e.g. [19]. The additional costs associated with dual-homing and protections at the ONU are generally considered too high in the cost-sensitive context of the access network to be a practical and economic option. However, the presence of a network of BSs which can be adaptively configured into a multiply-interconnected wireless mesh topology provides an important alternative back-up route through the NGOA network to the CO/CAN. Such a wireless mesh network can be achieved either by dedicated high bandwidth wireless links between BSs (e.g. at 60 GHz, to achieve the required multi-Gb/s throughputs), or by adaptive antennas and beam-shaping etc. (to efficiently exploit the available bandwidth capacity in a BS.) Such a possibility offers a convenient means for robust (redundant) protection and resilience in a fully-converged access network at minimum extra cost. Figure 2 indicates how such protection in the event of the failure of remote node RN$_1$, or a fibre cut immediately before RN$_1$, can be overcome by hierarchical transfer of data over a virtual wireless mesh network. In this case, a femto-cell can either relay directly to the local macro-cell BS, or via an intermediate micro/pico-cell. The macro-cell BS can then relay data to an adjacent macro-cell BS which then converts the data back into the optical domain, and transmits back up the PON via RN$_2$ towards the CO/CAN. Such a data pathway can operating in both upstream (US) and downstream (DS) directions; although US and DS can also be geographically split to follow different routes, according to local bandwidth and traffic requirements, and to balance network capacity resources across the network.

Figure 2: Converged access network featuring a hierarchical, wireless mesh topology suitable for robust and resilient protection in the event of individual fibre/RN failure.
5. CONCLUSIONS
In this paper, we have outlined the challenges associated with designing a fully-converged fixed-wireless network, featuring energy efficiency and optimised use of network resources. In particular, by adopting a hierarchical cellular wireless topology, we have indicated how robust network protection can be achieved, as well as additional energy efficiency advantages accrued. We have also indicated how the design criteria for next-generation optical access networks will have to be modified (e.g. with the presence and location of intermediate active equipment, for network cognition, content storage and distribution) to optimally allow for a fully-convergent fixed-mobile access network.

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