Design and Optimization of Fiber-Optic Small-Cell Backhaul Based on an Existing Fiber-to-the-Node Residential Access Network

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Abstract: As the number of wireless users and per-user bandwidth demands continue to increase, both the vendor and carrier communities agree that wireless networks must evolve toward more dense deployments. So-called "heterogeneous networks" are a commonly proposed evolution, whereby existing macro-cellular networks are supplemented with an underlay of small cells. The placement of new small-cell sites is typically determined based on various location-dependent factors such as radio propagation calculations, user densities, and measurements of congestion and demand. The backhaul network, which can account for a significant portion of the total cost of the deployment, is then designed in reaction to the placement of small cells. In contrast, we describe a design method which first considers the locations of existing fibered and powered facilities that might be leveraged to provide inexpensive backhaul. Naturally, such a method is only feasible if the carrier has a legacy local fiber network. This paper describes an efficient fiber backhaul strategy for a small-cell network, which leverages facilities associated with an existing fiber-to-the node (FTTN) residential access network. Once potential small-cell sites are determined from among all FTTN remote terminals (RTs), optimization techniques are used to choose the most efficient subset of sites for maximum coverage, and to design the fiber backhaul architecture.

1. Introduction

Telecommunication providers have addressed the ever increasing bandwidth demands of cellular radio networks with a series of wireless technology upgrades [1] and by adding cell sites (referred to as "macro-cell sites" in this paper). In AT&T's network, these upgrades have progressed through a long series of standards from AMPS to IS-54 digital AMPS (DAMPS) to IS-136 D-AMPS to GSM/GPRS to UMTS/HSPA+, with an upgrade to LTE nearly completed, resulting in an increase in per-user peak wireless bitrates from several kb/s to greater than 100 Mb/s under ideal conditions. Concurrent with this technology evolution, AT&T, like most other carriers, has added scarce (and costly) wireless spectrum. Despite this remarkable progress, the demand for the shared wireless channel continues to press the supply.

Naturally, increasing the peak rate of the radio link optimizes only one dimension of the wireless network design problem. Since radio spectrum is a finite resource, well designed networks must optimize the re-use of spectrum to maximize the number of simultaneous users. In addition to dividing cells into sectors, frequency re-use is increased by adding cells and thereby reducing the coverage area per cell. Thus, the tradeoff between cell tower density (i.e. total number of cellular base stations per area) and cost continues to be a key issue in the design of wireless networks [2]. While it is a foregone conclusion that operators must evolve toward a denser network of small cells, one big question is how to evolve to this dense micro-cellular deployment while minimizing investment in major cost contributors such as additional real estate and backhaul.

Like other large regional carriers, AT&T operates several networks, including a nation-wide wireless network and a broadband residential access network operating over a significant portion of the United States. In those areas where AT&T has deployed fiber-to-the-node (FTTN) access networks [3], the assets associated with the FTTN installation can be leveraged to provide fiber backhaul, right of way, and powering for upgrades to the wireless infrastructure. In this paper, we describe a strategy for augmenting the current macro-cellular wireless network with the addition of low-cost small cells collocated with existing FTTN remote terminals (RTs), and explore methods to optimize both small-cell coverage and the fiber backhaul architecture. Section 2 describes a method whereby candidate small-cell locations are automatically pre-selected from geo-coded FTTN data, based on an algorithm with selectable parameters such as radio coverage, proximity to existing macro-cell towers, population density, etc. Automating this process is critical, considering the vast number of network elements deployed in AT&T's FTTN

and wireless networks. Since this pre-selection process typically results in an overprovisioning of small cells, a heuristic solution to the maximum covering problem is described in Section 3. This approach permits the network designer to specify the number of small cells p from among the set of all pre-selected locations in a given geographic area, and then optimize coverage based on the particular choice of which p locations will serve as base stations. Since p is directly related to the total cost of the deployment, the best possible coverage can be derived as a function of cost. In section 4, the set of p small-cell sites that satisfy the maximum covering heuristic are the starting point for an access network optimization problem. Here, integer linear programming is used to design cost-efficient passive optical network (PON) deployments based on the in-place dark fibers associated with an existing FTTN network. Due to the sharing of valuable fiber assets, the resulting optimized PON deployments are shown to be more economical than conventional point-to-point fiber backhaul designs. The methods described in this paper focus on the efficient utilization of existing deployed assets. Some important considerations, such as the details of radio propagation including location-dependent signal power and interference must ultimately be considered, but are beyond the scope of this paper.

2. Network augmentation with small cells

Conventional wireless network planning methods place potential cell sites in "optimal" locations based on measured user data and propagation studies. In contrast to these methods, which typically require expensive new backhaul, powering and site acquisition, we start with the assumption that some fraction of new microcellular (or small cell) sites can be inexpensively deployed by collocation with previously fibered and powered network facilities, such as FTTN RTs. In our study area, macro-cell radii range from a few hundred meters to a few kilometers depending on propagation, traffic demand, geography, and other deployment constraints. Since it is well known that the radio link degrades with increasing distance from the cell tower, new small cells will be placed away from the centers of the existing macro-cell serving areas, thus supplementing the poor coverage near the macro-cell perimeter.
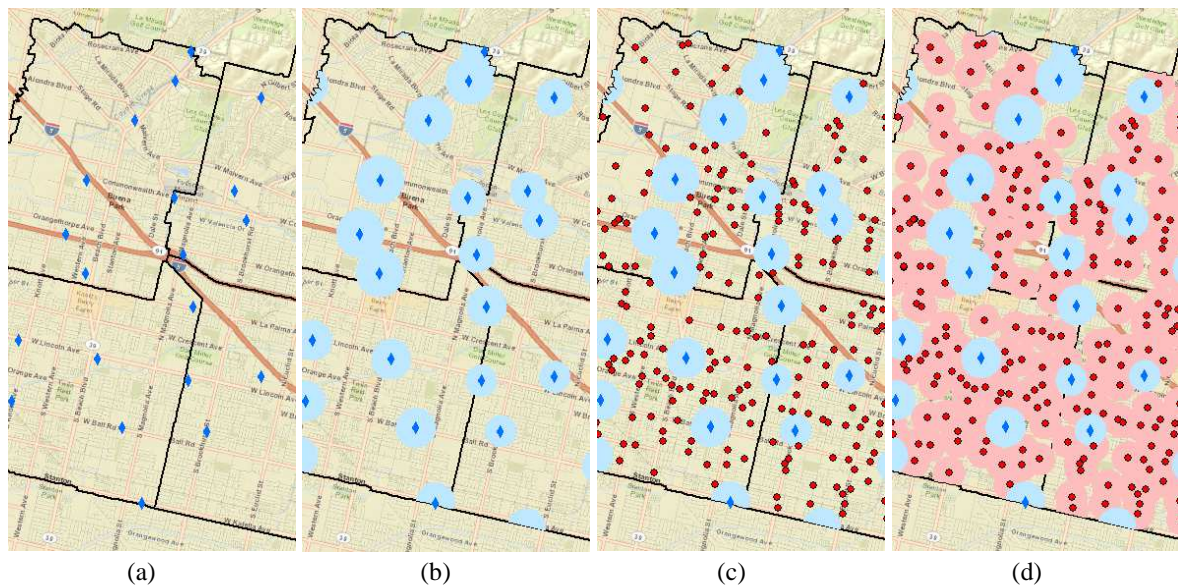

(a) (b) (c) (d)

Fig. 1: Sequence shows steps in the design process over a fraction of the study area: (a) map showing wire center boundaries. Blue diamonds are existing macro-cell sites (b) with nominal half-radius circles, sized based on density of macros per wire center (c) with RTs beyond macro half-radius coverage selected as potential micro-cell sites (d) nominal total coverage with 400-m small cell radii and macro half radii.

Our analysis and evaluations are based on network data for a typical urban/suburban area in the western U.S. Considering the size of the databases involved (for example, there are ~90,000 FTTN RTs over AT&T's nationwide local footprint), it is essential that efficient automated methods be devised to assist with the placement of small cells and the design of the backhaul network. The databases comprise demographic data, roads, FTTN access network infrastructure, macro cellular network infrastructure, etc. The study area, which consists of four adjoining wire centers served by both a broadband FTTN network and a wireless network, includes 705 FTTN RTs, which have fiber connectivity and power, and 84 macro-cell sites. Each fiber-fed RT is a potential location for an inexpensive omni-directional small cell with coverage radius of 400 m. To account for the effects of macro cells outside of the study area, the analysis also includes the macro base stations outside of that area but within 1 km of the area's

perimeter. Figures 1(a)-1(d) illustrate the design method over one portion of the study area, where wire center boundaries are shown as solid black lines. In order to efficiently upgrade the existing macro cellular network (cell sites shown by the blue diamonds in Fig. 1(a)), suitably located RTs must be identified. In this study area, 90% of neighboring RT distances are less than 600 m, so RT-based small cells with coverage radii in the 200 – 400 m range should be adequate for continuous coverage in most cases. Since users closest to existing macro cells experience the best performance, the small cells which are most useful for enhancing wireless service will be those located away from the center of an existing macro cell's coverage area. For this case ~80% of the RTs are located at a distance greater than 300 m from the nearest macro cell site, an indication that a large majority of the RTs are candidate base station locations for this enhancement strategy.

In our automated design process, we calculate a "nominal-coverage" macro-cell radius by dividing the area of a wire center (i.e. a central office serving area) by the number of macro cells in that wire center, resulting in a nominal per-cell area (and associated radius). This simplified approach is based on the assumption that the current macro-cellular network covers the area of most wire centers. Thus, the resulting wire center-dependent nominal macro-cell radii are reasonable estimates of actual coverage radii, and range from 782 to 1188 m over our four wire centers (nominal macro-cell radii are not shown in fig. 1). We assume that the central 25% of the area of each nominal-coverage circle (corresponding to half the nominal-coverage radius) has high signal to interference plus noise ratio (SINR) and does not need to be supplemented. Therefore all FTTN RTs except those within this half-radius are considered as candidate small cell sites. Thus, using these nominal-coverage areas as a starting point, we place supplemental RT-based small cells at distances greater than half the nominal-coverage radius from any neighboring macro cell (see Fig. 1(b) for half-radius macro coverage areas, and Fig. 1(c) for the subset of RTs beyond the macro half radii). Fig. 1(d) shows the coverage that can be achieved by deploying the entire resulting set of 442 small cells with radius of 400 m in conjunction with the existing macro cells at half radius. Note: Although the actual radio coverage for macro cells does not change, this representation makes it easier for the reader to see the added coverage associated with the small cells. These small cells can be deployed using a low-height (2-4 m) antenna mounted on or near the RT (for example on an adjacent light post) with low transmit power, while capitalizing on the available fiber backhaul over dark fibers associated with the FTTN network. Such a strategy may prove financially advantageous when compared with the cost of site acquisition, engineering and installation of traditional (macro) cell sites. Path loss calculations for typical omni-directional small cells with 250-mW transmitter power and 8-dB antenna gain indicate that the small-cell radii assumed in this study provide acceptable, and often better performance in suburban/urban areas with these low antenna heights [4,5], compared to typical macro-cell coverage.
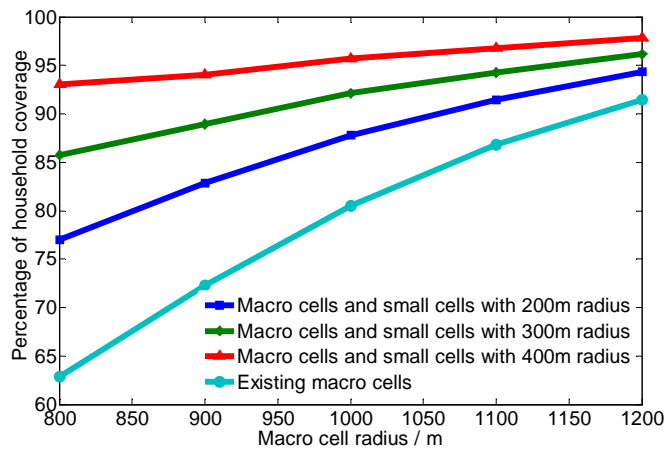

Fig. 2. Variation of coverage with macro and small cell radii

In Fig. 2, the percentage of households covered by deploying 200 m, 300 m and 400 m radius small cells in conjunction with the existing macro cellular network as a function of macro-cell radius is investigated. The total number of households in the study area exceeds 208,000. The figure shows significant improvements in coverage can be achieved using the RT locations to deploy small-cell sites, compared with the coverage that can be achieved using larger macro cells. For example, 83%, 89% and 94% household coverage can be achieved for 200 m, 300 m and 400 m small cells, respectively, in conjunction with 900-m macro cells, which correspond to 11%, 17 % and 22% coverage improvement, respectively. In addition to improving coverage area, adding additional cells increases the total available bandwidth and therefore the maximum number of simultaneous users.

It is important to note that the simplified circular coverage areas used in the above algorithm are proxies for more accurate coverage areas based on measured and calculated radio coverage associated with the existing macro-cellular network and the proposed small-cell locations. For such a calculation, each macro cell would be assigned a high-SNIR contour (analogous to the nominal half-radius circle) and only those FTTN RTs which fall outside of all such contours are chosen as candidate small-cell locations. The coverage of the resulting heterogeneous network (macro plus small cells) can then be estimated based on propagation model calculations of small-cell coverage contours.

3. Optimal Small Cell Location Problem

The method described above is a means for automatically extracting large numbers of candidate small-cell sites from geographic data bases. Whether using approximate circular coverage areas or more accurate measurement- and calculation-based coverage data, the assumption that all potential small-cell sites be used is potentially inefficient. Thus, we also present the results of a study which uses candidate small-cells, as determined above, as the initial conditions in solving the following maximum covering problem: Suppose we are given a set S of n potential sites on which to locate small cells and a set B of m city blocks, each with population $b_j \geq 0$, for $j = 1,\ldots, m$. Furthermore, suppose that for each site i that is an element of the set S we are given a set Γ_i of city blocks that would be covered if a small cell were to be deployed at site i.

In the *optimal small cell covering* problem we seek a subset, S^* of S, of the potential sites containing a given number of elements $p > 0$ such that if a small cell is deployed in each site in S^*, then the sum of the populations of covered city blocks is maximized.

Consider the example in Fig. 3 where there are nine city blocks and four potential small-cell sites: *a, b, c*, and *d*. Small-cell coverage is indicated by the shaded blocks. If only one small cell will be deployed, i.e. *p=1*, then the optimal choice is site *b*, since it alone covers 41 people while the other sites each cover fewer people. If two small cells are deployed, i.e. *p=2*, the optimal choice is *b* and *d*, since together these cells would cover 61 people while {*a,b*},{*a,c*}, and {*c,d*} each cover fewer. If three cells are to be deployed, i.e. *p=3*, then the optimal choice is *b, c,* and *d* which cover 79 people, while {*a,b,c*} and {*a,b,d*} each cover fewer. Finally if *p=4*, i.e. all cells are chosen, then 84 people are covered. Note that the incremental coverage decreases as more cells are deployed, going from a 48% increase from *p=1* to *p=2*, to a 29% increase from *p=2* to *p=3*, to only a 6% increase going from *p=3* to *p=4*.
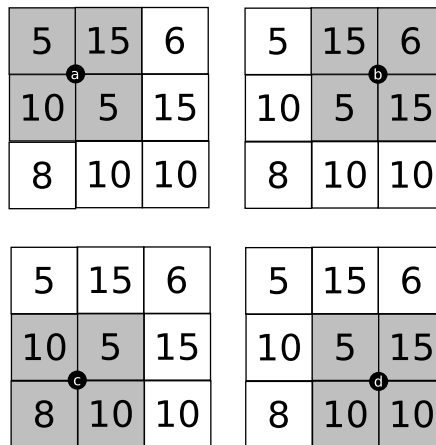

Fig. 3: Example small cell covering problem. There are four potential small cell sites (*a*, *b*, *c*, and *d*) and nine city blocks, each with its corresponding population. The shaded blocks are those that would be covered if a small cell were to be deployed.

Finding the optimal deployment configuration by enumeration is only feasible for very small instances. As the number of potential sites and city blocks increases, one needs to resort to an optimization algorithm. The small cell covering problem is a *maximum covering* problem and integer programming formulations for it exist. However, the problem is NP-hard, implying that as the problem size increases, integer programming will eventually not be able to find the optimal solution to the problem. In such situations, one often resorts to heuristics. Several heuristics for maximum covering have been proposed in the literature, e.g. [6-8]. A very efficient software for maximum covering is POPSTAR [9], which formulates the maximum covering problem as the NP-hard *p-median* problem and applies

GRASP with evolutionary path-relinking heuristic for *p*-median described in [10]. It can quickly find optimal and near-optimal solutions to small cell covering problems having thousands of potential cell locations and tens of thousands of city blocks.

Consider an instance of the small cell coverage problem in the western U.S. with 613 potential cell sites and 4212 city blocks where we consider a small cell site to cover a city block if the centroid of the block is no more than 400 meters from the cell site (here we use U.S. Census data to determine the location and associated population of households in the study area). If all cells are deployed then 95.3% of the population is covered (Some city blocks are more than 400 meters away from any potential cell site). Running POPSTAR for *p*=1, 2,…, 613 results in the coverage shown in Fig. 4 (a). With as few as about 300 small cells, maximum coverage is achieved. Fig.4 (b) shows coverage with the deployment of 300 small-cell sites. In spite of achieving over 95% coverage with the deployment of 300 sites, this solution does not cover a large number of city blocks. This implies that most of these blocks are sparsely populated, accounting for less than 5% of the population.
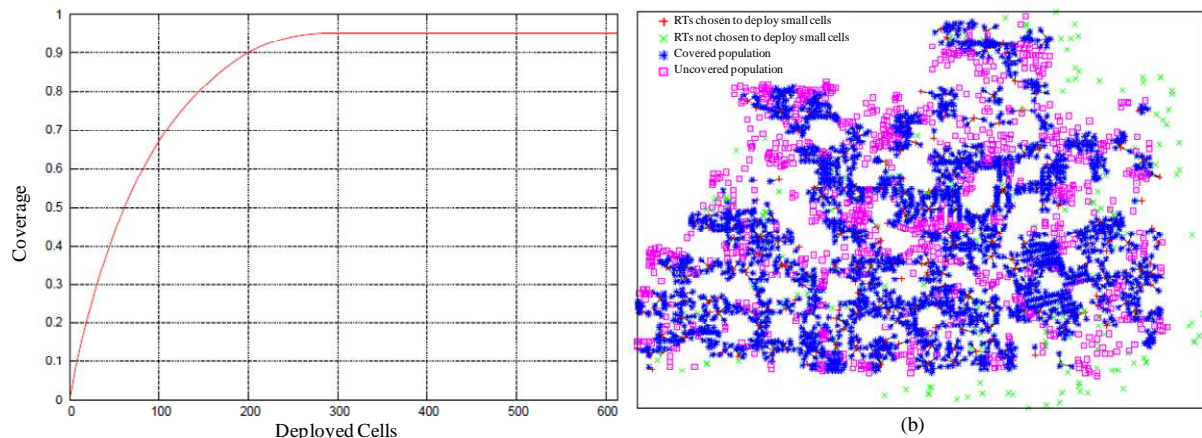

Fig. 4. Results of solving the maximum covering problem (a) coverage (b) graphical illustration

4. Fiber Backhaul Architecture Optimization

The results of the maximum covering method described above, a set of *p* small cell locations collocated with existing powered and fibered network facilities, can be considered the input to a backhaul-network design problem: Given the existing number and locations of available dark fibers in a particular wire center serving area, what is the best choice of dark fibers, splice locations, and backhaul architecture to most efficiently (i.e. cost-effectively) backhaul these *p* sites? Here, we describe an additional study that uses linear integer programming (ILP) [11] to optimize the design of passive optical networks (PON) to provide fiber backhaul to the small-cell sites [12]. The capabilities of PON access architectures to share fibers, central office equipment and bandwidth among end terminals (i.e small cells in this scenario), make them potential candidates to backhaul small cells cost-effectively. Nevertheless, each of the components in the PON needs to be planned and placed optimally in order to maximize its benefits. To this end, an optimization framework is developed based on ILP, which guides the cost-optimal deployment. Green field scenarios for PONs which provide fixed broadband access have previously been studied [13, 14]. However, planning the positioning of PONs on top of an existing fiber infrastructure for small cell backhauling is more complex, as one also needs to consider the existing available infrastructure. In AT&T's local network, each FTTN RT is connected to a multi-fiber cable that was installed as part of the FTTN build-out. These multi-fiber "distribution" cables have ample available dark fiber, but generally do not link all the way back to the central office (CO). Rather, they are connected, via intermediate splice points, to fiber trunks emanating from the CO. Since the total number of dark fibers available in these trunks is typically fewer than the total number of dark fibers summed over all of the FTTN distribution cables, care must be taken to use these trunks as efficiently as possible (keeping in mind that all as yet unforeseen future local fiber builds will rely on dark fibers in these trunks to connect to the CO). Thus, PONs represent an appealing means for backhauling a large number of small cells in a given wire center, while sharing valuable CO trunk fibers (also referred to as "feeder" fibers in typical descriptions of PONs). From here on we focus on planning a cost-optimal PON-based fiber backhaul network, using a more conventional point-to-point backhaul arrangement as a benchmark, noting that PONs use bidirectional single fiber connections, while point-to-point (PTP) fiber installations typically use up and down fiber pairs.
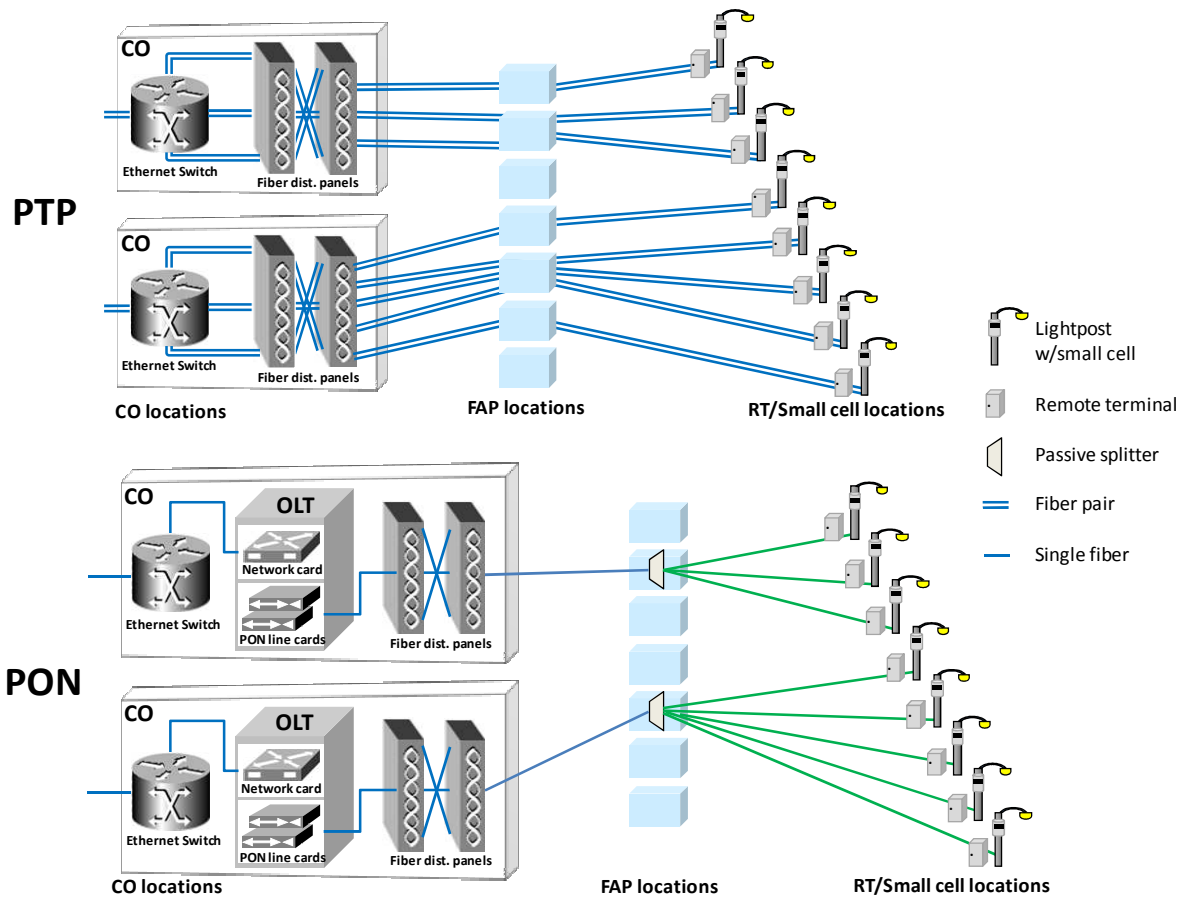
Fig. 5. PTP and PON backhaul architectures

Fig. 5 shows typical PTP and PON deployment scenarios. For PTP, pairs of fibers for each RT/small cell are used to connect back to their respective network equipment in the CO. In contrast, the PON consists of three primary components, the optical line terminal (OLT), the optical network terminal (ONT) and the passive optical splitter. The OLTs are installed at the central office (CO) and connect with the metro network via the metro terminal equipment co-located at the CO. The ONTs are placed at the FTTN RTs where the small-cell base stations are deployed. The ONTs are connected to the OLTs using existing single fibers by appropriately placing passive optical splitters in the fiber path. The fiber located between the OLT and the splitter is commonly referred to as the feeder fiber, while the section between the splitter and the ONT is known as the distribution fiber. Since the PON-based backhaul network is an overlay on the existing infrastructure, the splitters need to be installed where the fiber is accessible (e.g. fiber access points or FAPs) such as in manholes, splice boxes, etc.

Let **C** denote the set of CO locations, **O** the set of small cell locations, and **F** the set of FAP locations. The objective is to design a cost-optimized PON-based backhaul for all locations of **O** using existing fiber resources by optimally choosing a subset of **F** for the splitter placement and selecting a subset of **C** for the OLT installations. When formulating the optimization framework, all of the network requirements and all of the costs involved in the PON deployment are taken into account. In terms of network parameters, firstly the fiber split ratio is considered. The split ratio depends on different network requirements such as the required small cell backhaul capacity. Assuming, for example, that the PON equipment adheres to the GPON standard [15], approximately 2.5 Gb/s of downstream bandwidth is available to be shared among all small-cell sites connected to a PON. Three different split ratios (1:4, 1:8, 1:16) are examined for such a real-world example. Secondly, the maximum transmission distance which determines the span of a PON is taken into account and it depends on both the power budget and the split ratio. To operate properly, the total length of the feeder and the distribution fibers should not exceed the maximum

transmission distance. With regard to cost, the components can be broadly categorized into fiber, equipment and labor. For fiber, the standard time value of money approach is used to determine the value of already installed fibers. The value of the fiber depends on the type and length that will be used for the deployment. Therefore, the costs will differ for distribution and feeder fibers and must be considered separately. The equipment involved in the PON-based backhaul network deployment is primarily categorized into three types based on where the equipment is installed or used in the network; 1) At the CO, there is the OLT consisting of the components depicted in Fig. 5: an Ethernet switch and fiber distribution panels or fiber cross-connects. There will be a fixed cost per connection. 2) Each splitter resides at a FAP that includes the cost of the first splitter and associated enclosures. 3) The ONT which is located at the RT location to backhaul the small cell. As for labor, there is a cost associated with any splitter installation, in particular, the cost to send personnel to the FAP and for the splicing itself. There will also be additional labor costs for work performed in the CO. The optimization framework takes into account all of the aforementioned cost elements when planning a PON-based backhaul for small cells overlaid to an existing infrastructure. A detailed description of the ILP-based optimization framework has been previously reported [12].

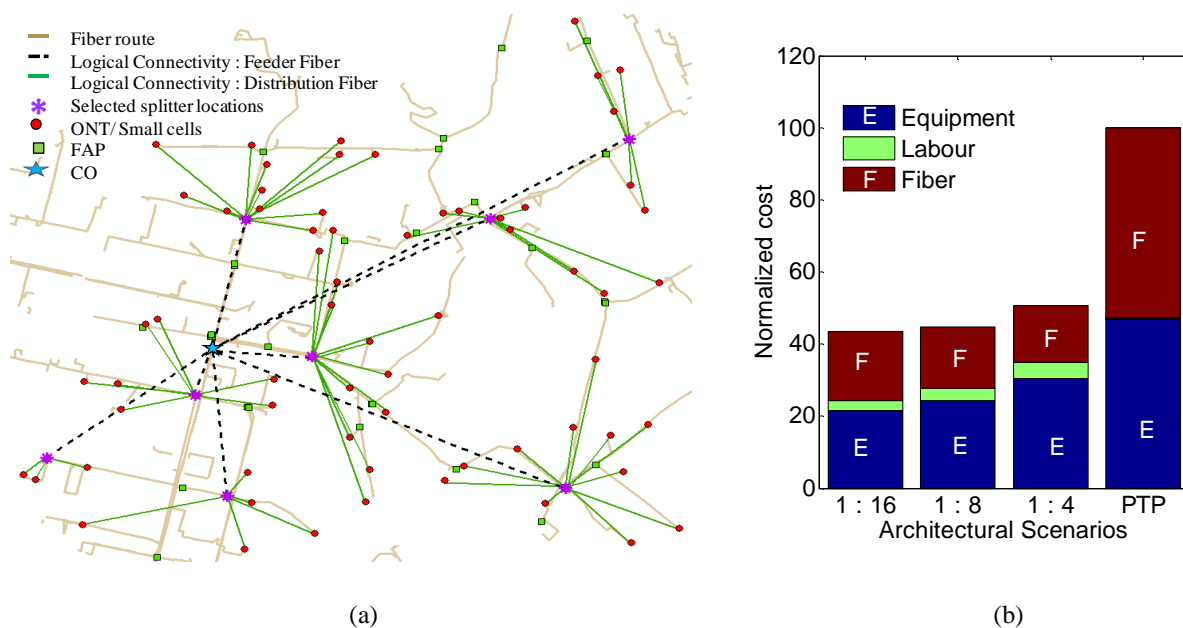(a)   (b)

Fig. 6: (a) Optimal solution for 1:16 split deployment scenario (b) Normalized deployment cost of different architectural scenarios

Fig. 6 (a) shows the network dataset we use to analyze our test case. This dataset covers one CO serving area of AT&T's existing FTTN network. For this dataset, we use our optimization framework to determine the most the cost-efficient PON-based backhaul solutions for a range of split ratios. For example, the optimal solution obtained for 1:16 split deployment scenario is overlaid in Fig. 6(a). The corresponding splitter locations are denoted by asterisks while the logical connectivity of optimally selected feeder and distribution fibers is denoted by black dashed and solid green lines respectively.

In Fig. 6(b), we compare the total deployment cost of a typical PTP deployment scenario and the optimal PON-based solution under different split ratios. In addition to the total deployment cost, Fig. 6(b) also shows the cost contribution of each major cost component involved in the deployments. Note that the values shown in Fig. 6(b) are normalized with respect to the total deployment cost of the PTP solution such that the total deployment cost of the PTP solution is 100. In contrast to green field deployments, where labor is typically the dominant cost, Fig. 6(b) shows that the main cost contributor in the optimal PON-based deployment is the equipment cost. Conversely, the main cost contributor in the PTP deployment is the fiber. Moreover, the deployment costs of the PON-based solution increase when the split ratio decreases. In particular, the equipment and labor costs increase while the fiber cost decreases as the split ratio decreases. This occurs because the number of splitter locations and the number of PONs that are required for such a deployment are increased, resulting in higher costs for equipment and labor. Overall, for this test case, the cost of the optimal PON-based solution saves more than 50 % of deployment cost in comparison to that of the PTP case.

Naturally, the success of such a small cell approach hinges on a low-cost deployment. Based on estimates of the outlays associated with macro cell deployments, such as large capital costs, leasing cell premises, backhauling, powering, maintenance and engineering, we are encouraged that the augmentation using small cells in conjunction with an existing FTTN network has favorable economics and performance, thus warranting further detailed study.

5. Conclusion

The increasing demand for high bandwidth applications and the rapid development of high-end user devices will strain cellular service providers' ability to offer ubiquitous and high-speed access to customers. Achieving this with existing macro-cellular wireless infrastructure is economically challenging due to the high capital and operational costs associated with network upgrades. To provide enhanced access in a cost-effective way, we study the deployment of small cells collocated with a subset of existing FTTN RT locations, thus leveraging available electrical power and fiber backhaul facilities. By adding small cells only around the periphery of existing macro cells, both coverage and total network capacity can be improved. Choosing from among all potential small-cell locations is accomplished with a computationally efficient heuristic solution of the optimal small-cell covering problem. The choice and design of an efficient passive optical network architecture to backhaul these sites, based on an existing fiber infrastructure, are determined by an integer linear programming optimization. The results of these studies indicate a means exists for the economical deployment of a broadband microcellular underlay to an existing macro-cellular network.

5. References

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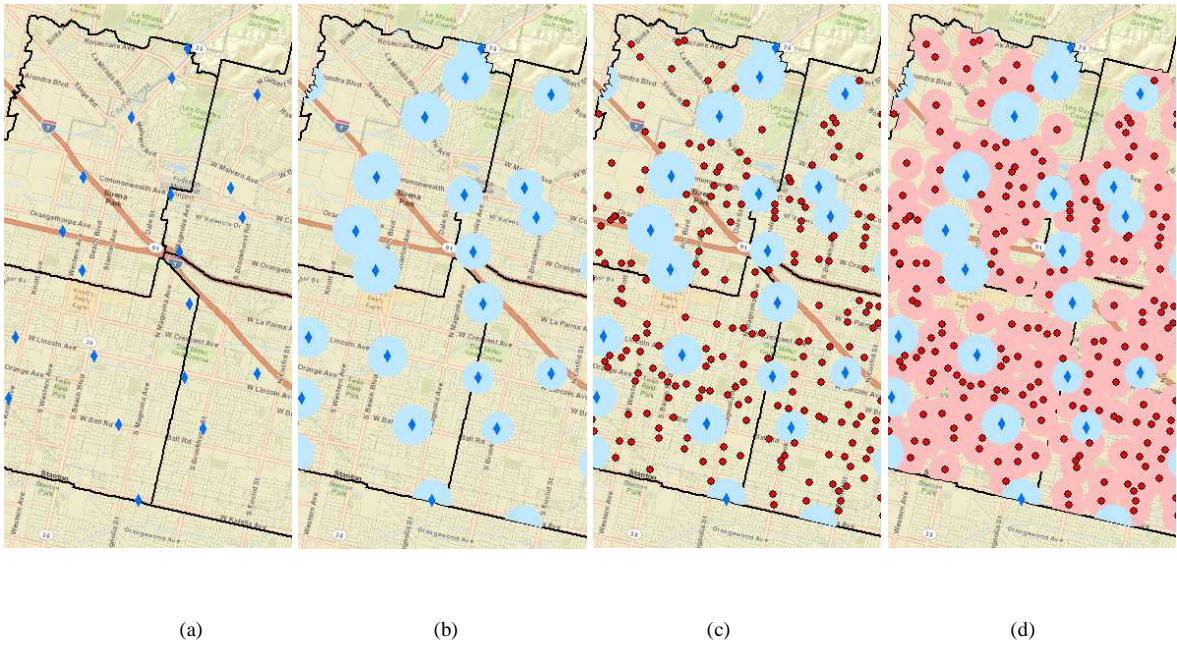
(a) (b) (c) (d)

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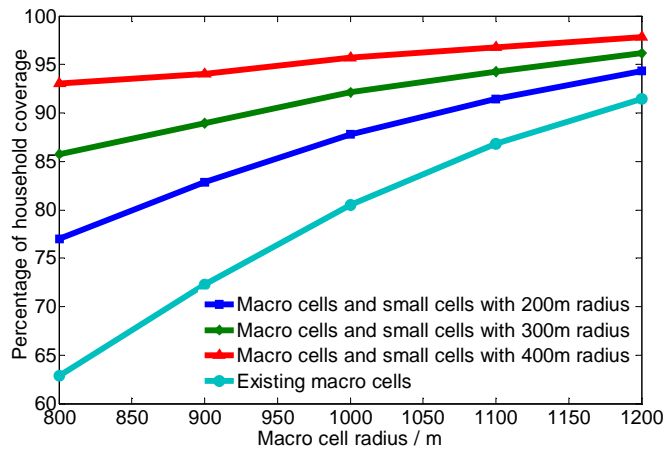
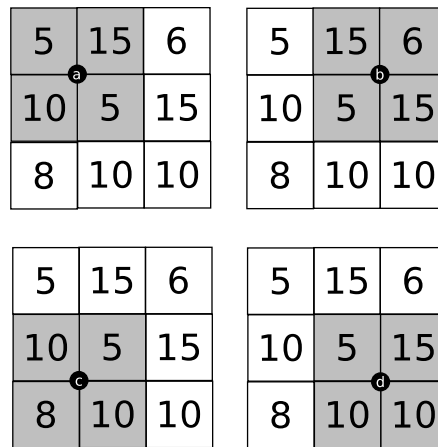Fig. 2. Variation of coverage with macro and small cell radii

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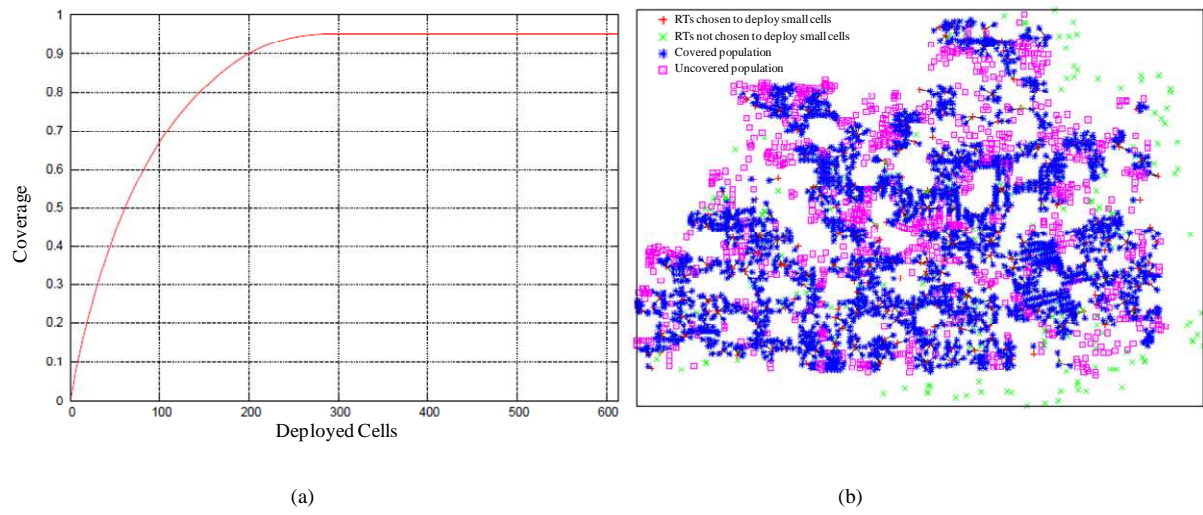|	
(a)	(b)

Fig. 4. Results of solving the maximum covering problem (a) coverage (b) graphical illustration

PTP

PON

CO

Ethernet Switch

Fiber dist. panels

CO

Ethernet Switch

Fiber dist. panels

CO locations

FAP locations

RT/Small cell locations

CO

OLT

Network card

PON line cards

Ethernet Switch

Fiber dist. panels

CO

OLT

Network card

PON line cards

Ethernet Switch

Fiber dist. panels

CO locations

FAP locations

RT/Small cell locations

Lightpost w/small cell

Remote terminal

Passive splitter

Fiber pair

Single fiber

Fig. 5: PTP and PON backhaul architectures

	Fiber route
	Logical Connectivity : Feeder Fiber
	Logical Connectivity : Distribution Fiber
	Selected splitter locations
	ONT/ Small cells
	FAP
	CO

(a)

(b)

Fig. 6: (a) Optimal solution for 1:16 split deployment scenario (b) Normalized deployment cost of different architectural scenarios