

Wireless Optical Convergence Enables Spectrum-Energy Efficient Wireless Networks

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Abstract—The most effective solution to simultaneously improve both spectrum efficiency (SE) and energy efficiency (EE) is a small-cell structured wireless network such as distributed antenna network (DAN). Instead of using centralized antennas at macro-cell base station (BS), antennas are spatially distributed and are connected via coherent optical links to signal processing center (SPC) (which is equivalent to macro-cell BS). Although DAN is actually small-cell structured, SPC and its distributed antennas form a virtual macro-cell. The channel between SPC and a user terminal can be treated as an equivalent wireless channel. Therefore, handover problem in a small-cell network can be replaced by antenna selection problem within a virtual macro-cell transceiver of SPC. The deployment density of SPCs can be made similar to the present macro-cell network. In this paper, we will discuss SE-EE tradeoff of a cellular network using frequency reuse and show the potential improvement of SE-EE tradeoff introduced by the small-cell structured network. Then, we will describe DAN concept forming virtual macro-cell and heterogeneous DAN overlaid by macro-cells.

Keywords—wireless optical convergence, spectrum-energy efficiency tradeoff, distributed antennas, 5G wireless network

I. INTRODUCTION

Our modern society is heavily relying on communications networks. Almost everyone is always connected to the network. Due to rapid penetration of smart phones into our society, broadband data services are getting more and more popular. Since the available frequency bandwidth is limited, the enhancement of spectrum efficiency (SE) has been the most important concern for the last few decades. However, since the available energy is also limited, the energy efficiency (EE) is also attracting a hot attention recently [1]. Note that in this paper, only the radiated signal energy from antenna(s) is considered although the total energy consumption including power amplifier (PA), signal processing, and data transfer is also important [2]. It is well-known that SE and EE are in a tradeoff relationship [3]. How to simultaneously improve both SE and EE is an important issue. The most effective solution to achieve this is a small-cell structured wireless network [4]. However, simply densifying the deployment of base stations (BSs) may bring significant increase in control data traffic among BSs because of frequent handover due to user mobility. To avoid these problems, the wireless access network may

need significant restructuring. One possible solution is a distributed antenna network (DAN) [5-7], or distributed antenna system (DAS) [8,9], where the antennas are spatially distributed instead of using centralized antennas at macro-cell BS and are connected via coherent optical links to signal processing center (SPC) (which is equivalent to macro-cell BS). All the signal processing, resource allocation, and scheduling are performed at SPC. Although DAN is actually small-cell structured, SPC and its distributed antennas form a virtual macro-cell.

In this paper, we will discuss SE-EE tradeoff of a cellular network using frequency reuse and show the potential improvement of SE-EE tradeoff introduced by the small-cell structured network. Then, we will describe the DAN concept forming virtual macro-cell. As a practical solution, 2-layer heterogeneous network consisting of DAN and macro-cells will be introduced.

II. WIRELESS EVOLUTION

How has the wireless evolved in the last three decades and where will it go in the future?

The 1st generation (1G) public wireless networks using analog technology appeared in 1990's. This dramatically changed the communications networks from fixed "point-to-point" communications to wireless "anytime and anywhere" communications. Since then, new generation networks appeared almost every 10 years and evolved from 1G to 3G networks [10]. Figure 1 shows how the wireless networks have evolved and how they will evolve in the future. Currently 3.9G networks, called long term evolution (LTE), have been under rapid deployment worldwide. In a few years, we will see the deployment of 4G networks called LTE-advanced.

During the last three decades, the wireless networks have evolved from narrowband networks of a few kbps to wideband networks of around 10Mbps. Now we are on the way to broadband networks of above 100Mbps. In 1G and 2G networks, voice conversation was the dominant communication service. High speed data services including video are popular in 3G and will become more and more popular in 3.9G. As indicated in Fig. 2, the wireless traffic volume is growing explosively by about 2 times per year [11].

This suggests more than 1,000 times growth in the coming 10 years. However, the available wireless bandwidth is limited. How to cope with such an explosive growth of wireless traffic while the available frequency bandwidth is limited? This is a very important issue.

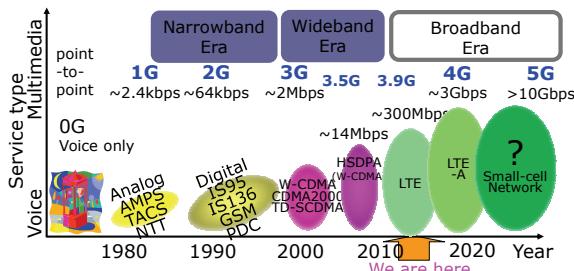


Fig. 1 Wireless evolution.

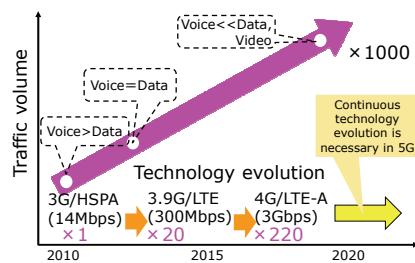


Fig. 2 Explosive growth of wireless traffic.

III. SPECTRUM- AND ENERGY-EFFICIENCY TRADEOFF

A. Area spectrum efficiency (ASE)

In the case of point-to-point wireless communications, it is important to increase the SE defined by bps/Hz. However, in the case of cellular type wireless networks, important is to increase the area spectrum efficiency (ASE) [12] defined by bps/Hz/km² (this definition is used throughout the paper). To efficiently utilize the limited bandwidth (i.e., improving the SE), the same frequency needs to be reused at as close locations as possible [13]. However, the frequency reuse causes a serious problem of co-channel interference (CCI). Hence, the CCI becomes a limiting factor to the SE and thus, the CCI management becomes a crucial issue. Increasing the SE has been the most important issue during the last few decades. In any practical networks, BSs are deployed in an irregular location layout due to difficulty in finding BS locations. For the ease of understanding the frequency reuse, let's assume a regular hexagonal cell layout. The model of frequency reuse [13] is shown in Fig. 3.

ASE η_{ase} in bps/Hz/km² is defined as

$$\eta_{\text{ase}} = C \times \frac{1}{F} \times \frac{1}{S}, \quad (1)$$

where C denotes the channel capacity in bps/Hz, F the frequency reuse factor, and S the cell size in km². Assuming N_c -subcarrier orthogonal frequency division multiplexing (OFDM), C can be represented as

$C = (1/N_c) \sum_{n=0}^{N_c-1} \log_2(1+\lambda_n)$, where λ_n denotes the channel gain at the n th subcarrier [14]. Using Jensen's inequality [15], we have

$C \leq \log_2(1 + \sum_{n=0}^{N_c-1} \lambda_n / N_c) \approx \log_2(1 + \Lambda)$ owing to the law of large numbers, where Λ is the signal-to-CCI plus noise ratio (SINR). Reducing the value of F (i.e., the same frequency is reused at nearer locations) increases the CCI, thereby reducing the value of Λ . As a consequence, F and Λ are related to each other. Assuming the single-user and worst case scenario (the user is located at the cell edge), F and Λ are related each other as $F = [1 + (6\Lambda)^{1/\alpha}]^2 / 3$ [13]. Substituting this into Eq. (1), η_{ase} becomes

$$\eta_{\text{ase}} = 3 \frac{\log_2(1 + \Lambda)}{\{1 + (6\Lambda)^{1/\alpha}\}^2} \times \frac{1}{S}. \quad (2)$$

Figure 4 plots η_{ase} as a function of Λ with the propagation path loss of $\alpha = 3.5$. Interestingly, $F=1$ (single frequency reuse) does not maximize the ASE, because too strong CCI is produced. η_{ase} is maximized at F of around 4~7. Therefore, each BS can utilize only a fraction of the system bandwidth. To improve the SE, the application of multi-input multi-output (MIMO) spatial multiplexing [16] has been gaining an increasing attention. The use of M transmit and M receive antennas improves the ASE by almost M times.

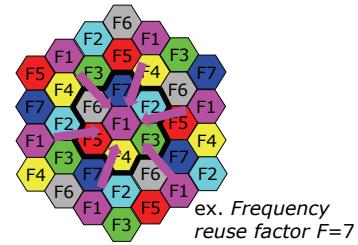


Fig. 3 Frequency reuse model ($F=7$).

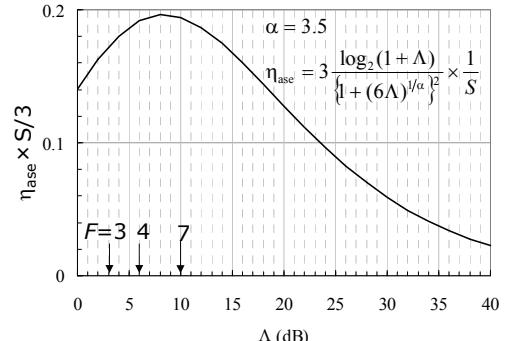


Fig. 4 Area spectrum efficiency η_{ase} .

B. SE-EE Tradeoff

Broadband wireless services are getting more and more popular in line with an increasing popularity of smart phones. Since the available bandwidth is limited, the SE is becoming

more and more important. However, another important issue arises. Higher rate data transmission requires higher transmit power. This is a heavy burden for battery operated mobile terminals. Also significantly increased is the energy consumption in the whole network, i.e., access network and core network. Therefore, recently, strong attention has also been paid to EE in addition to SE. We should remember that increasing the transmit signal power strengthen the CCI and hence, reduces η_{ee} . Therefore, ASE η_{ase} bps/Hz/km² and EE η_{ee} bits/Joule are in a tradeoff relationship.

After some manipulation, we obtain (their derivation omitted)

$$\left\{ \begin{array}{l} \eta_{ase} = \frac{1}{F} \times \log_2 \left(1 + \frac{1}{\Gamma_r^{-1} + 6(\sqrt{3F} - 1)^{-\alpha}} \right) \times \left(\frac{1}{(3\sqrt{3}/2)R^2} \right), \\ \eta_{ee} = \Gamma_r^{-1} \times \log_2 \left(1 + \frac{1}{\Gamma_r^{-1} + 6(\sqrt{3F} - 1)^{-\alpha}} \right) \times \left(\frac{A \cdot T \cdot R^{-\alpha}}{N_0} \right) \end{array} \right. , \quad (3)$$

where $\Gamma_r = (A \cdot P_t \cdot T / N_0) \times R^{-\alpha}$ represents the received signal-to-noise ratio (SNR) at the cell edge with A being a constant representing antenna gain and feeder loss, P_t the transmit power, $1/T$ the data symbol rate, and R the cell radius. Figure 5 plots SE-EE tradeoff with F as a parameter for the given R . No transmit power control (TPC) [17] is assumed. The figure clearly shows that the SE-EE tradeoff exists. By increasing the transmit power (equivalently increasing the received SNR Γ_r), SE improves (because the noise impact can be mitigated), however, EE degrades rapidly. It seems that $F=4$ achieves the best tradeoff. It is interesting to note that EE does not degrade so rapidly as far as too high SE is not demanded.

TPC is a powerful means to avoid too excessive transmit power by keeping the received SNR at a prescribed target value Γ_{tpc} and therefore, to save the signal energy. η_{ase} and η_{ee} with TPC are given by (their derivation omitted)

$$\left\{ \begin{array}{l} \eta_{ase} = \frac{1}{F} \times \log_2 \left(1 + \frac{1}{\Gamma_{tpc}^{-1} + (A^{-1}\beta)6(\sqrt{3F} - 1)^{-\alpha}} \right) \times \frac{1}{(3\sqrt{3}/2)R^2} \\ \eta_{ee} = (\beta\Gamma_{tpc})^{-1} \times \log_2 \left(1 + \frac{1}{\Gamma_{tpc}^{-1} + (A^{-1}\beta)6(\sqrt{3F} - 1)^{-\alpha}} \right) \times \frac{A \cdot T \cdot R^{-\alpha}}{N_0} \end{array} \right. \quad (4)$$

with

$$\beta = \exp \left(\frac{\sigma^2}{2} \left(\frac{\ln 2}{10} \right)^2 \right) \times \frac{L}{M \cdot L - 1}, \quad (5)$$

where σ , M , and L denote the standard deviation of log-normally distributed shadowing loss, the number of receive antennas, and that of resolvable propagation paths,

respectively. SE-EE tradeoff with TPC when $M=1$ and $L \rightarrow \infty$ is plotted in Fig. 6. Much better tradeoff than without TPC is obtained. $F=4$ is clearly seen to achieve the best tradeoff.

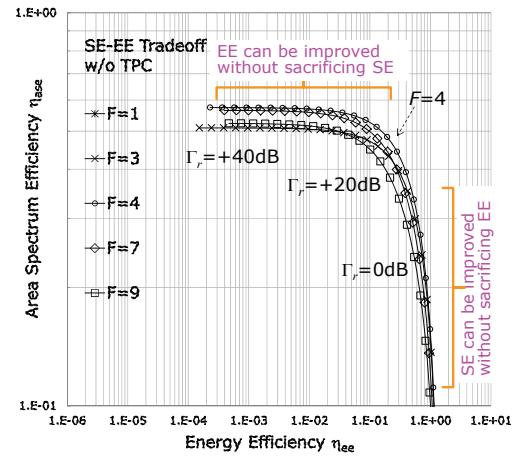


Fig. 5 SE-EE tradeoff without TPC.

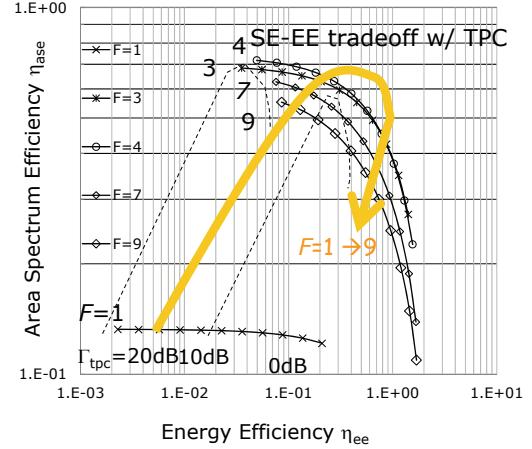


Fig. 6 SE-EE tradeoff with TPC.

IV. DISTRIBUTED ANTENNA NETWORK (DAN)

We, human being, share the same bandwidth of about 4kHz on the globe of approximately 7 billion people to make voice conversations. This is a good example of the ultimate single frequency reuse ($F=1$). However, for the single frequency reuse, suppression of the CCI is a problem. The key to minimize the CCI is the short range communication which allows transmissions of low signal energy. Hence, SE-EE tradeoff can be improved. However, an important technical issue exists: how to integrate short range communications into a network? For designing spectrum and energy efficient wireless networks, it may be an important hint from our human being's voice communications that no tight coordination among people is

applied, although TPC like voice control is inherently adopted by people.

A. Small-cell structured network improving SE-EE tradeoff

How to improve SE-EE tradeoff is an important issue of future wireless networks. An important hint can be obtained from Eq. (4); both the efficiencies can be simultaneously improved by reducing the cell size R . One solution is an adoption of a small-cell structured network. Reusing the same frequency at near locations can significantly improve the SE. The transmit power of user terminal can be significantly lowered, thereby improving the EE.

SE-EE tradeoff computed using Eq. (4) is plotted in Fig. 7 with the cell-size reducing factor r (≤ 1) as a parameter when the propagation path loss exponent $\alpha = 3.5$. With TPC, reducing the cell size is quite effective to improve SE-EE tradeoff. Reducing the cell size by a factor of 10 (i.e., $r=0.1$) results in about 100 times improvement of SE. EE improvement is more than SE improvement and is more than 1,000 times (however, note that only the radiated signal energy from antenna is considered in this paper). It is clear that the key to improve SE-EE tradeoff is to adopt short range communications. Recently, we have extended the SE-EE analysis to DAN case [18].

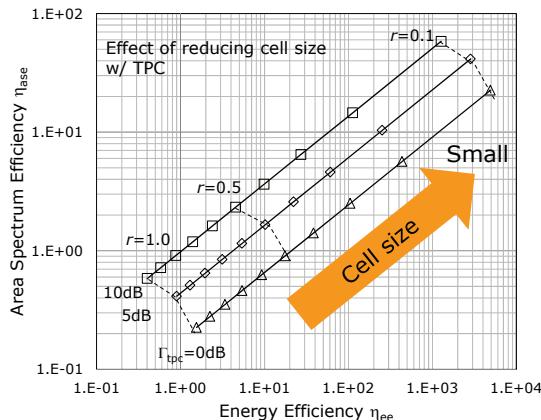


Fig. 7 SE-EE tradeoff with cell radius as a parameter.

How to integrate short range communications into a network? This will be discussed in detail in the following subsections. However, simply reducing the cell size has a problem. Since frequent handovers increases control data traffic among BSs and users. This is particularly problematic for high mobility users. This means that simple adoption of small-cell structured network cannot be recommended. How to realize small-cell structured network while alleviating a problem of increased control data traffic? Significant restructuring of wireless access network is necessary.

B. DAN concept

One promising realization of small-cell structured network is a distributed antenna network (DAN) [5-9]. Present macro-

cell BS is equipped with co-located multiple antennas for cell-sectorization and antenna diversity. In DAN, many antennas are distributed over entire macro-cell area as shown in Fig. 8. Only some of distributed antenna(s) close to a user are activated to form a very small wireless cell centering each user, i.e., personal wireless cell is formed. By doing so, the path loss and shadowing loss problem can be alleviated as well as multipath fading problem.

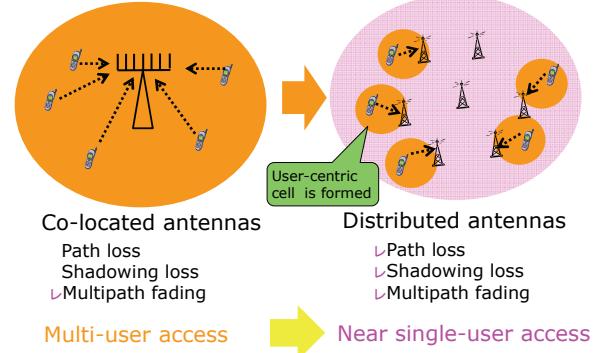


Fig. 8 Distributed antenna concept.

Figure 9 illustrates the conceptual structure of DAN. Present macro-cell BS is replaced by a signal processing center (SPC). Each distributed antenna is connected with a SPC by coherent optical link. Although DAN is actually small-cell structured, SPC and its distributed antennas form a virtual macro-cell. All the signal processing, resource allocation (frequency, time, power, and antenna) and scheduling are performed at SPC.

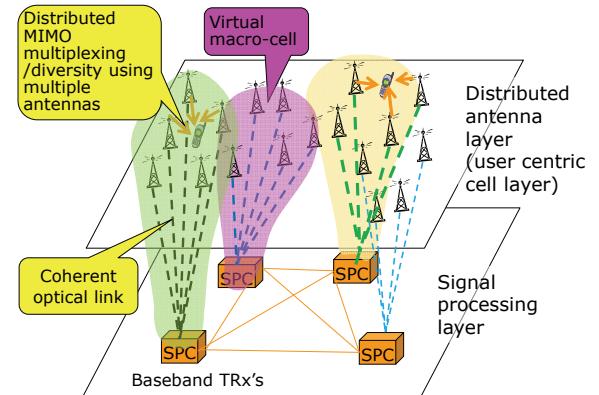


Fig. 9 DAN conceptual structure.

C. A new type of SDMA

SPC is a virtual macro-cell transceiver which serves users in an SPC area (present BS cell). Let us consider the uplink transmission. The received signals at distributed antennas transmitted from users in a virtual macro-cell can be described as

$$\mathbf{R} = \mathbf{H}\mathbf{X} + \mathbf{\Pi} \quad (6)$$

with

$$\mathbf{H} = \begin{pmatrix} H_{n,m} \end{pmatrix}, H_{n,m} = \sqrt{A \cdot P_m \cdot d_{n,m}^{-\alpha} \cdot 10^{-\delta_{n,m}/10}} h_{n,m}$$

$$\mathbf{X} = \begin{pmatrix} x_0 \\ \vdots \\ x_{M-1} \end{pmatrix}, \quad \mathbf{\Pi} = \begin{pmatrix} \pi_0 \\ \vdots \\ \pi_{N-1} \end{pmatrix}, \quad (7)$$

where \mathbf{H} denotes an $N \times M$ channel matrix between N distributed antennas and M users (note that the frequency nonselective channels are assumed for the sake of brevity). $h_{n,m}$, $d_{n,m}$, and $\delta_{n,m}$ denote the channel response, distance, and shadowing loss, respectively, between the n -th distributed antenna and the m -th user. \mathbf{X} and $\mathbf{\Pi}$ denote the transmit signal vector and noise vector, respectively. As an extreme case, let's consider the case of $N > M$ (more distributed antennas than users). Letting the transmit power of each user small enough, only the antenna closet to the user can receive the signal with a sufficient power due to different path losses among different antennas. Therefore, \mathbf{H} can be approximately written as

$$\mathbf{H} = \begin{pmatrix} H_{0,0} & \cdots & 0 \\ 0 & \ddots & \vdots \\ 0 & 0 & H_{M-1,M-1} \\ \vdots & & \vdots \\ 0 & \cdots & 0 \end{pmatrix}, \quad (8)$$

where the users are re-ordered according to the antenna index. Eq. (8) clearly indicates that the users can be separated by antennas. User separation (or multi-access) problem can be replaced by antenna selection (or antenna activation) within a virtual macro-cell transceiver of SPC. Signal processing in virtual macro-cell transceiver at SPC is similar to that in the present BS transceiver. However, very low delay optical link between SPC and distributed antenna is required.

Selection of spatially distributed antennas based on user location (or received signal level) is equivalent to a new type of space division multi-access (SDMA). Of course, in a real environment, off-diagonal elements in Eq. (8) may not be zero, but the elements far from the diagonal elements may be negligibly small. Therefore, although multi-access technique is needed, simple multi-access technique of small number of users can be applied.

Another extreme case is the present macro-cell network with centralized antennas, in which \mathbf{H} can be described as

$$\mathbf{H} = \begin{pmatrix} H_{0,0} & \cdots & H_{0,M-1} \\ \vdots & \ddots & \vdots \\ H_{M-1,0} & & H_{M-1,M-1} \\ \vdots & & \vdots \\ H_{N-1,0} & \cdots & H_{N-1,M-1} \end{pmatrix}. \quad (9)$$

In this case, multi-access technique (FDMA, TDMA, CDMA) or multi-user detection (MLD, MMSED) of large number of users is necessary.

Short range communication combined with near single-user access is the crucial requirement for maximizing the SE.

This can be realized by increasing the number of distributed antennas per SPC. Since only a few users tend to access the same distributed antenna, multi-access problem of large number of users may be alleviated. An extreme case is that single user can occupy the whole bandwidth, thereby increasing the data rate. Furthermore, short distance access makes it possible to use new frequency bands like mm-wave band, where abundant bandwidth remains unused. Since the attenuation of signal is quite high in such a frequency band, it is practical to combine the high frequency band with massive antenna concept [19].

D. Virtual macro-cell formation

The transmit power is adaptively controlled by TPC so as to meet the required quality of service (QoS). Instead of antenna selection, if the same signal of a high mobility user is transmitted from and received by all of distributed antennas simultaneously, a virtual macro-cell can be formed. This is done if transmitting timing difference is controlled within the cyclic prefix (CP) length for block transmissions (i.e., OFDM, SC-FDE, etc.) with frequency-domain equalization. Of course, multi-access technique (FDMA, TDMA, CDMA) is needed. In this way, DAN can serve high mobility users. Handover between virtual macro-cells (or SPCs) is necessary, but this can be done similarly to present cellular networks.

E. Coherent optical link

The optical link between SPC and each distributed antenna can be implemented by using either radio over fiber (RoF), Common Public Radio Interface (CPRI) [20] for baseband I/Q transmission over optical fiber, or digital coherent optical transmission [21,22]. The use of RoF link allows all radio functions to be installed at SPC. However, nonlinearity of RoF link causes a serious problem. CPRI allows analog baseband I/Q signals to be transmitted over optical fiber between SPC and distributed antenna equipped with radio frequency modulator/amplifier; but very high speed baseband transmission of multi-Gbps is required over fiber. On the other hand, the use of digital coherent optical communication allows to treat the optical transmission and wireless transmission similarly; the difference between two is only the carrier frequency as shown in Fig. 10. The concatenation of optical link and wireless link can be treated as an equivalent wireless link if the same data modulation is used over both the optical link and wireless link. Therefore, the channel matrix can be described by Eq. (6).

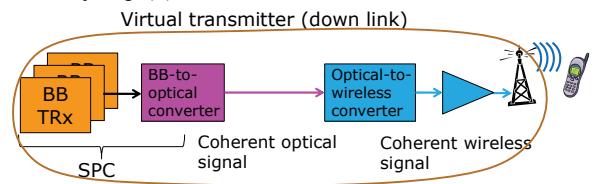


Fig. 10 Coherent optical link between SPC and distributed antenna. Downlink case.

V. HETEROGENEOUS DAN

Probably an entire area of SPC may not be able to be covered by low-power distributed antennas. This is problematic for reliable connection control. To avoid this problem, an introduction of 2-layer heterogeneous DAN, as shown in Fig. 11, overlaid by macro-cells may be a realistic approach. In 2-layer heterogeneous DAN, small-cell layer covers hot-spot area and macro-cell layer covers wide area.

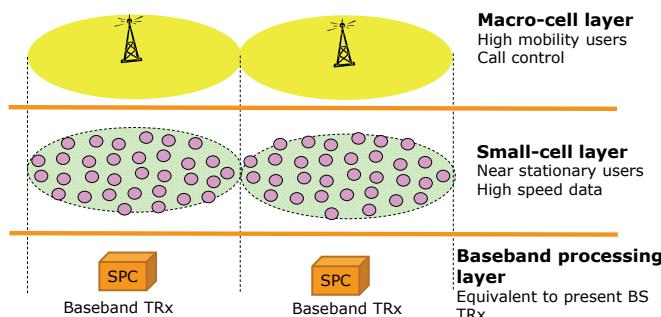


Fig. 11 2-layer heterogeneous DAN.

An inherent nature of a wide range of user mobility is problematic. For high mobility users, frequent handover between small cells (or frequent antenna re-selection within a virtual macro-cell transceiver of SPC) may happen. Increasing the control data traffic significantly reduces the capacity of data traffic. Traditional macro-cell structured network may be suitable for high mobility users. Furthermore, the traffic distribution is not uniform and there may be only a few scattered hotspot areas of heavy traffic. Heterogeneous DAN overlaid by macro-cells may be a practical solution. To alleviate the problem of increasing control data traffic in DAN, an adoption of similar concept to the phantom cell concept (separation of control data and user data paths) [23] is a good idea. The control data traffic is carried by a traditional macro-cell structured network and broadband data traffic is carried by a small-cell structured network like DAN.

VI. CONCLUSIONS

In this paper, we discussed SE-EE tradeoff when using the frequency reuse and showed the potential improvement of SE-EE tradeoff introduced by the small-cell structured network. Then, we introduced the DAN concept forming virtual macro-cells. As a practical solution, 2-layer heterogeneous DAN overlaid by macro-cells was introduced; small-cell layer to cover hot-spot area and macro-cell layer to cover wide area.

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