"CENTRAL PROCESSING / REMOTE RF" FOR CELLULAR NETWORKS, USING OPTICAL MICROCELLS: CONCEPT AND PERFORMANCE

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ABSTRACT

This paper presents the "Central Processing / Remote RF" concept for designing cellular networks in dense urban areas, using RF heads connected to a central office via fiberoptics. This concept is made possible by developments in optical technology, which allow the conversion of RF signals to light and their transport via fiberoptics with very low loss and distortion, and by the expansion of fiber networks in urban areas. This technology, called "RF-on-fiber (RoF)", makes possible the concentration of all the base station processing in a central office, connected via fiberoptics to simple low-power RF repeaters at the cell sites. This architecture opens new possibilities in the design and implementation of cellular networks. It provides significant flexibility in upgrading functionality, and implementing various wireless standards and air interfaces, consistent with the goals of an SDR approach. The paper includes optical link performance calculations, such as gain, noise figure, spurious-free dynamic range, showing examples of typical specifications. Also discussed are resource savings due to central processing aggregation.

1. INTRODUCTION

Current and next generation cellular wireless systems are becoming increasingly complex in their ability to deliver capacity, low latency and cost effectiveness for the operator. Using "RF on fiber" technology [1][2], a centralized cellular system can offer significant value added services to the customer as well as be able to accommodate future air interfaces to truly enable a world of SDR. Some of the potential advantages of such a system are listed below.

- Flexibility in upgrading the functionality and implementation of various wireless standards and air interfaces. Allows operator equipment sharing.
- Significant reduction of the cost of equipment and installation of the RF units at the cell site, since the hardware at a site is just a small enclosure and an antenna.
- Significant reduction in cost of equipment, due to fewer constraints in size, power, and heat dissipation at the central office.
- Reduced "Cost of Ownership" through recurring savings for upgrades, site rental, power consumption, air-conditioning, and maintenance.

- Central processing could utilize reconfigurable processing elements for the greatest flexibility at a low cost.
- The central processing office allows direct high-speed connectivity between base stations, thus facilitating CDMA algorithms such as fast cell site selection, fast handovers, scheduling, load management, and power control.
- Improvement in the quality of service by the dynamic allocation of resources, such as channel processing elements
- By pooling processing resources (trunking gain), an overall reduction of 20% in channel elements can be obtained.
- Flexibility in deploying and expanding the network, since all the resources are concentrated in one location.
- Enables new revenue generating services such as dispatch and "walkie-talkie" features. These types of new services are difficult to implement with current systems.

  The main disadvantages of this concept are:
- The implementation of the network requires the laying of optical fiber. Therefore, the cost of deployment depends on the availability of the fiber backhaul.
- The concentration of all processing in one location requires special attention to safety, reliability and redundancy issues. Fault tolerance must be taken into account when designing the central processing architecture.

2. SYSTEM CONFIGURATION

2.1. RoF Link Configuration

The connection between the central office and the access point is via optical fiber, and the signal transported is analog RF at the carrier frequency. Figure 1 shows a simple RoF link.
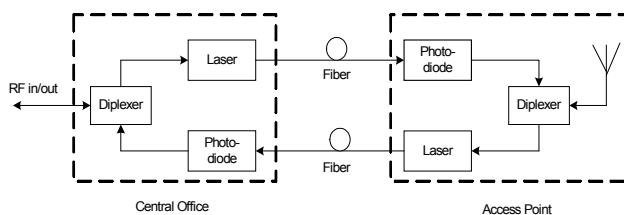

Figure 1: Typical RoF Link

At the central office, the RF signal is applied directly to the laser, modulating its light intensity. The laser is either in the 1310 nm or 1550 nm windows of low loss fiber. The fiber is usually of the single mode type. The optical receiver is a photo-diode of the PIN type, which translates the optical power to RF. This type of link is known as "intensity modulated – direct detection (IM-DD)".

The access point is a simple low-cost "optical microcell," as shown in Figure 2.
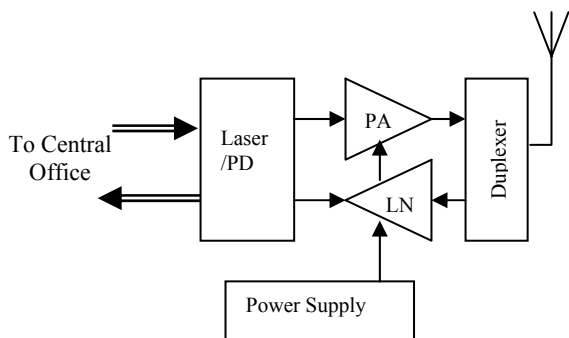
Figure 2: Optical Microcell

The optical microcell includes an omni antenna, a duplexer, a low power amplifier on the downlink (~1 W), a low noise amplifier on the uplink, a laser on the downlink, a photo-detector on the uplink, and a DC power supply. Except for the antenna, all the components can be realized on a small printed circuit, enclosed in a weatherproof enclosure. For diversity combining, some of the components can be duplicated in the same package. Multiple cells can use the same optical backhaul, by using WDM (Wavelength Division Multiplex) techniques [3]. The access point can be installed on top of light poles, or on building walls. Reduction in antenna size can be obtained by using a dual-polarized antenna.

Given the broad bandwidth of the optical link, the access point can be implemented as multi-band/multi-mode, covering the cellular, PCS and WLAN bands. Figure 3 shows the basic configuration.
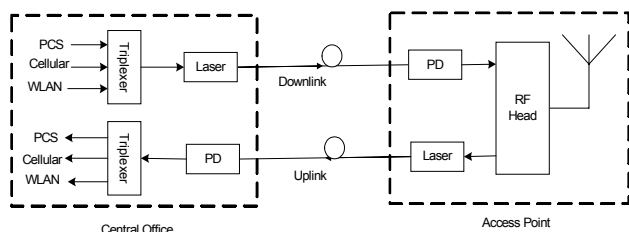
Figure 3: Basic Multi-band Configuration

2.2. Central Processing Performance Benefits

The concept of central processing means that the processing electronics for the entire network is located in a central office. For example, the multi-cell base station (MCBTS), the Mobility Manager (MM) and the Transcoder in CDMA or the RNC in UMTS, and the 802.11 processing units, could all be in the same location. The difference between these units is actually blurring, and a processing architecture can be designed to perform the functionality of all these units by one common computer. The following is a discussion on the performance benefits of central processing.

- **"Ultimate" SDR**: With central processing, the access point can be designed to support multiple standards and services simultaneously, without the need for control. The signals can be separated at the central office, and processed accordingly. One or multiple operators may share the central office, supporting cellular, PCS and WLAN services simultaneously.

- **Resources aggregation**: The design of current base stations contains resources (channel processing elements) sufficient to answer the need for peak capacity demand in each cell. In reality, the demand for capacity is flexible, depending on location, time of day, special events, etc. By aggregating the resources from multiple cells in one location, we have the ability to allocate them according to changing needs. Furthermore, in section 3 we calculate that due to aggregation statistics, we can save up to 20% of resources, for the same quality of service.

- **Scheduling**: One of the critical issues in data services is to optimize the scheduling of packet data service to users, based on RF conditions and available capacity. Several scheduling schemes have been proposed: "Round Robin", which sends packets equally to each user, "C/I based", which schedules according to C/I, and "Fair C/I", which balances between the two methods. Accurate "Fair C/I" scheduling requires continuous information of RF conditions from all users. It is much simpler and faster to perform these scheduling algorithms in the central office, since all the information and the resources are in one place.

- **Fast cell site selection**: This is a major feature proposed for UMTS, as part of future 3GPP releases. It enables fast selection of the optimum cell site, saving resources and allowing high data rates. With the standard network configuration, the implementation of this feature is a major challenge, because it requires high-speed communication between base stations and the central office. Central

processing architectures will make the implementation of this feature much simpler.

- **Fast handoff**: This is related to the previous item. Once fast cell site selection is possible, we can significantly reduce the handoff time. This is especially critical with microcells, where the subscriber mobility requires handoffs more often. Since multiple cells are controlled by one MCBTS, all handoffs between these cells become "softer handoffs".

- **Outer loop power control**: This feature is related to changing the set point of the outer loop power control according to mobile speed, propagation conditions, and type of service. It requires communication between the base station and the RNC. If all processing is performed centrally, outer loop power control can be implemented more efficiently.

- **Downlink power control**: This feature was introduced in 3G to reduce interference from the base station. A problem rises when the mobile unit is in handoff, and integrates the signal from multiple cells. In this case the power control command generated by the mobile unit applies to all the cells to which it communicates, irrespective of their contribution to the signal, possibly causing power drift between base stations. In a central office implementation, this information is known, and more intelligent algorithms may be developed for power control.

- **Dispatch**: Motorola has pioneered the direct-connect feature in the iDEN system, which can provide additional services and revenues to the operator. Unfortunately, the 3G standards do not address the specific latency and processing requirements for this mode, but through central processing, this feature can be integrated into the cellular system.

- **SDR and Equipment Sharing**: Software Definable Radio (SDR) and equipment sharing were initiated to reduce the deployment costs incurred by operators. It requires the ability to operate on different standards and carriers. The implementation of this ability in a conventional BTS is very complex and costly. This becomes much simpler in a centralized processing center.

3. RESOURCES SAVINGS DUE TO AGGREGATION

When systems are aggregated to a central location, there are savings because the pool of resources required is less than the sum of the required individual resources. The following illustrates the potential for equipment savings due to aggregation or trunking.

3.1. Distributed Processing System

At a given base site, there is a certain call volume per hour. This can be expressed in number of busy minutes per hour at a given site. This volume has a mean μ, and standard deviation σ, in Erlangs. One Earlang is considered a single voice channel occupied continuously. For a base site to handle all its traffic with a 99.9% service level (i.e., so it can handle all the traffic at that cell site 99.9% of the time during a busy hour), the capacity must be about 3.09 standard deviations above the mean (standard normal distribution). The total number of channels y for n cells is then given by:

$$(1) \quad y = n\mu + 3.09\sigma n$$

For example, let us assume the maximum a given base station can handle is 128 voice channels, for a capacity of 128 Erlangs. If we assume the statistics for the mean and standard deviation representative of busy hours, from say 8am-4pm, we can get a handle on the call requirements exhibited at a given base site. For example, if we assume that the average total call volume for a given base site is 100 Erlangs, with a standard deviation of 9 Erlangs, then to achieve a 99.9% level of service, the base station needs to support 127.8 Erlangs. To accommodate 200 base stations of processing, a brute force method would be to put 25,562 Erlangs worth of processing at the central office.

3.2. Central Processing System

Now assume that instead of processing each call with a base station at each site, we now have a call center. Suppose all the physical layer processing from the base site is performed centrally, so that the processing center supports 200 base sites. If it is assumed that the total call volume is normally distributed, and that the call volume random variables are independent from site to site, then the capacity x that needs to reside at the call processing center for 99.9% service level is given by:

$$(2) \quad x = n\mu + 3.09\sigma\sqrt{n}$$

In our example it results in 20,393 Erlangs. If this is compared to the 25,562 Erlangs utilized for the distributed system, it is seen that there are about 20% less resources required at the call center to provide the same level of service. This all happens because the variance of the aggregate processing center goes up by the square root of the number of base sites per call processing center. The more microcells are connected to a single central office, the higher the savings due to aggregation.

Note that the savings increase with larger variances and larger number of base sites. To calculate % savings

based upon different levels of service, the value of 3.09 can be replaced with the number of standard deviations required for a given service level.

4. OPTICAL LINK CALCULATIONS

In this section we calculate the optical link performance, and assess its compatibility with cellular systems requirements [4][5]. The optical link is comprised of a laser, a length of fiberoptics, and a photodetector. The laser is of the DFB (distributed-feedback) type, directly modulated by the RF carrier, the fiber is single-mode, and the photodetector is a PIN diode. The optical link is cascaded with RF amplifiers. The total link performance depends on the optical link performance, which in turn is related to the optical components specifications. The critical parameters for the optical link are gain, noise figure, and spurious-free dynamic range (SFDR).

4.1. Gain
The gain is given by:

$$(3) \quad G = \frac{S_L^2 S_D^2 R_D}{L_o^2 R_L}$$

where:
S_L – laser slope efficiency [mW/mA]
S_D – photodetector responsivity [mA/mW]
R_L – laser impedance
R_D – photodetector impedance
L_o – fiber optical loss

It is notable that the RF loss is double the optical loss, in dB. For typical $S_L = 0.08$ mW/mA, $S_D = 0.9$ mA/mW, $R_L = R_D = 50$ ohm and $L_o = 5$ dB (0.5 dB/Km for 10 Km), the gain is:
  $G = -32.85$ dB.

4.2. Noise Figure
The noise figure can be expressed as:

$$(4) \quad NF = 10\log\frac{N_{in}}{kT}$$

where N_{in} is the total noise spectral density at the link input, k is Boltzman's constant, and $T = 270^oK$. There are three sources of noise: laser noise, photodetector noise (shot noise) and thermal noise. Typically, the thermal noise is negligible.
The laser noise is given by:

$$(5) \quad N_L = \frac{RIN * P_o^2 R_L}{S_L^2}$$

where:
RIN – laser Relative Intensity Noise
P_o – optical power

For typical values of RIN = -155 dB/Hz and P_o = 10 mW, we obtain N_L = 2.47E-16 or -156 dBW/Hz.
The photodetector shot noise is given by:

$$(6) \quad N_D = 2qR_DP_oS_D/G$$

where q = 1.6E-19 coulomb (electron charge). For the typical values, we obtain N_D = 2.78E-16 or -155.6 dBW/Hz.
The typical noise figure is therefore:

$$NF = 10\log[(N_L + N_D)/kT] = 51.5 \text{ dB}$$

We can see that because of the high noise figure of the optical link, we need a low-noise/high-gain preamplifier on the uplink.

4.3. Spurious-free Dynamic Range
The SFDR is defined as the range of the two input signals in which the signals are above the noise floor, and the third-order products are bellow the noise floor. The SFDR is related to the third order intermodulation product level, and is given by:

$$(7) \quad SFDR = 2/3(IIP_3 - NF - kT - B) \text{ [dB]}$$

where:
IIP_3 – input 3rd order intermodulation in dBm
B – bandwidth in dBHz

A typical value for an optical link is IIP_3 = 25 dBm. For the noise figure calculated above, we obtain:

  SFDR = 98 dB/Hz [2/3]
and for B = 5 MHz, we obtain:
  SFDR = 53 dB [2/3]

4.4. Cascaded Performance
Following the performance calculations for the optical link, we can now calculate the performance of the entire cascade, comprised of amplifiers, filters, optical link, etc. The cascaded values of the NF and IIP_3 can be calculated according to the following expressions:

$$(8) \quad NF_{tot} = NF_1 + \frac{NF_2 - 1}{G_1}$$

where:
  NF_{tot} – cascaded noise figure

NF_1 – noise figure of the previous stage
NF_2 – noise figure of the current stage
G_1 – gain of the previous stage

$$(9) \quad \frac{1}{IIP3_{tot}} = \frac{1}{IIP3_1} + \frac{G_1}{IIP3_2}$$

where:

$IIP3_{tot}$ – cascaded IIP3
$IIP3_1$ – previous stage IIP3

$IIP3_2$ – current stage IIP3

Using the values for the optical link and typical values for components comprising the front end, we calculated the cascaded parameters for the downlink and uplink. We considered a bandwidth of 5 MHz, and assumed an input signal of -20 dBm for the downlink, and –90 dBm for the uplink. The results for the downlink and uplink are shown in tables 1 and 2, respectively.

Table 1: Downlink Cascaded Parameters

	Input Parameters				Cascaded Output Parameters						
Component	Gain (dB)	NF (dB)	IIP3 (dBm)	OIP3 (dBm)	Gain (dB)	Signal Level (dBm)	Noise Level (dBm)	SNR (dB)	NF (dB)	IIP3 (dBm)	SFDR (dB 2/3)
Amp	30.0	4.0	8.0	38.0	30.0	10.0	-72.9	82.9	4.0	8.0	73.9
Optical Link	-33.0	51.5	25.0	-8.0	-3.0	-23.0	-88.3	65.3	21.6	-5.2	53.4
Amp	40.0	4.0	-2.0	38.0	37.0	17.0	-48.2	65.2	21.7	-6.1	52.7
BPF	-2.0	2.0	52.0	50.0	35.0	15.0	-50.2	65.2	21.7	-6.2	52.7

Table 2: Uplink Cascaded Parameters

	Input Parameters				Cascaded Output Parameters						
Component	Gain (dB)	NF (dB)	IIP3 (dBm)	OIP3 (dBm)	Gain (dB)	Signal Level (dBm)	Noise Level (dBm)	SNR (dB)	NF (dB)	IIP3 (dBm)	SFDR (dB 2/3)
BPF	-2.0	2.0	52.0	50.0	-2.0	-92.0	-106.9	14.9	2.0	52.0	104.6
LNA	40.0	2.0	-2.0	38.0	38.0	-52.0	-64.9	12.9	4.0	0.0	68.6
Optical Link	-33.0	51.5	25.0	-8.0	5.0	-85.0	-87.9	2.9	14.0	-13.2	53.1
Amp	30.0	4.0	8.0	38.0	35.0	-55.0	-57.8	2.8	14.0	-13.3	53.0

For both links the cascaded SFDR is about 53 dB $^{2/3}$, which is compatible with the 3GPP requirement of 45 dB ACLR [6]. More work needs to be done, performing tests and measurements using commercial equipment, including WDM components, to validate that the performance of the optical link is adequate for meeting the 3G standards.

5. CONCLUSIONS

The deployment of fiber-optics backhaul in most cities, combined with the technology of transporting analog RF on fiber, has the potential of providing an alternative to the current cellular network architecture, at higher flexibility and lower cost. Centralized processing, combined with low-cost remote RF units, open a new realm of design and implementation possibilities for multi-band/multi-mode applications, consistent with SDR goals.

6. REFERENCES

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