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Investigations of coverage and energy efficiency in radio-over-fiber distributed antenna systems

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Summary

In this work, the energy efficiency of a Distributed Antenna Systems (DAS) using radio-over-fibre (RoF) transmission is assessed against a conventional mono-antenna system. The power consumption of a Wi-Fi access point and dongle are measured to compute simulations using distance-dependent energy efficiency model. The simulations show that a distributed system with four antennas is almost twice more energy-efficient than a centralized mono-antenna system.

1. Introduction

Capping the power consumption of mobile and wireless networks, whilst accommodating growth in the number of subscribers, has become a crucial issue in view of the growing need for un-tethered and ubiquitous connectivity. Within that context, new strategies for greener telecoms are being extensively researched to reach higher energy efficiency and greater power saving, not only for terminals to increase their battery life, but also for access points to reduce their carbon footprint.

Furthermore, demands on throughput and performance keep on increasing, with extended coverage especially in indoor environments such as homes and public places (stadiums, commercial centres, transport hubs) where users are densely located.

Distributed Antenna Systems (DAS) are known to improve coverage [1] and performance of wireless communications in indoor environments. One approach for reaching higher energy efficiency consists in forming smaller coverage cells by reducing the transmit power at each antenna site [2]. A future-proof and high-capacity optical communication network can be advantageously provided to interconnect all antenna sites. In that case, radio-over-fibre (RoF) transmission techniques are used to transport optically high bit-rate radiofrequency (RF) signals. The main advantages of RoF distributed antenna systems include very low fibre transmission loss, large bandwidth, and low transmit RF power levels, which enable us to improve the coverage of in-building wireless services [3].

In this paper, our aim is to study the energy efficiency issue within RoF distributed antenna systems and to compare it with a centralized antenna system.

2. Coverage

2.a. Indoor propagation model

For optimum coverage, performance, and energy efficiency [4], an accurate RF propagation model [5] and design methodology [6] are required to position the distributed antennas. Although indoor radiofrequency (RF) propagation has been extensively studied, the received RF power cannot be accurately predicted. Shadowing effects, multiple scattering and reflections from obstacles such as walls and furniture cause strong time and space variations in received power.

The RF propagation model used in this work is statistical and does not require any topographical data. Indeed our goal is not to find quantitative results, but to evaluate possible energy consumption discrepancies between the centralized antenna and DAS schemes. Therefore, we shall use a simple model to estimate the RF power received by the receiver as a function of distance.

The average received power can be expressed (in dBm) as :

$$P_r = P_t + G_t + G_r - PL \qquad \textbf{Eq. 1}$$

where P_t is the transmit power in dBm, G_t and G_r are the transmitter and receiver antenna gains, respectively, and PL is the path loss in dB. Considering isotropic antennas, $G_t = G_r = 0$ dBi and the path loss is given by the following equation [7]:

$$PL = PL(d_0) + 10n\log_{10}\frac{d}{d_0} \qquad \textbf{Eq. 2}$$

where $PL(d_0)$ is the path loss at d_0=1m, $PL(d_0)$=40.2dB at 2.4GHz, *d* is the distance between transmitter and receiver and *n* is the power decay index. Considering a dense environment with small rooms, typically an office where each employee has his/her own office, the power decay index is between 4 and 6 [7]. In our simulations, we shall use *n*=4, which is adapted to cluttered environments.

2.b. *Data rate reachable*

Regarding the Wi-Fi standard, the modulation scheme is adjusted according to the received power level. When a modulation is selected, the maximum reachable data rate is set by the IEEE 802.11 standard. Datasheets of Wi-Fi access points or Wi-Fi cards provide the relationship between the modulation used and the receiver sensitivity with corresponding bit-rate. For illustration purposes, some of these data are presented in Table 1 for a Netgear Access Point [8].

Standard	Data rate	Receiver sensitivity
802.11b	1 Mbps	-93 dBm
802.11b	11 Mbps	-89 dBm
802.11g	24 Mbps	-84 dBm
802.11g	36 Mbps	-80 dBm
802.11g	48 Mbps	-76 dBm
802.11g	54 Mbps	-75 dBm

Table 1. Maximum data rate given by the 802.11 standard relative to the power received by the terminal (box/dongle) [8].

2.c. *Simulations*

A map of the highest reachable throughput as a function of distance was computed based on the above indoor propagation model and the receiver sensitivity provided in datasheets. The size of the area under consideration is 40m×40m.

In a first step, Figure 1 shows the evolution of the reachable throughput as a function of the distance between the access point and the mobile terminal, with a total radiated power of 6dBm. The maximum data rate given by the 802.11 standard is reached over 21% of the total area.

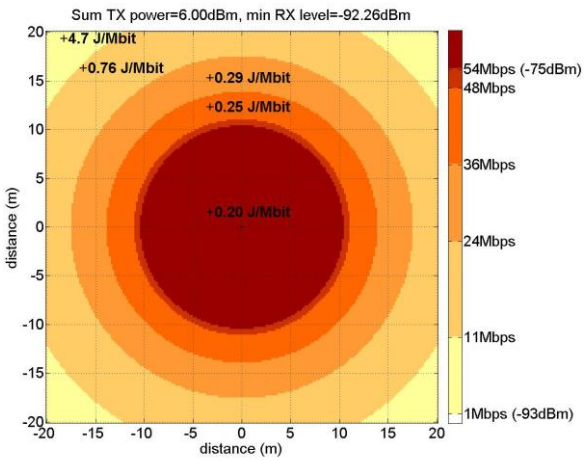

Figure 1. Map of the highest 802.11 reachable data rate with one access point, considering a total radiated power of 6 dBm

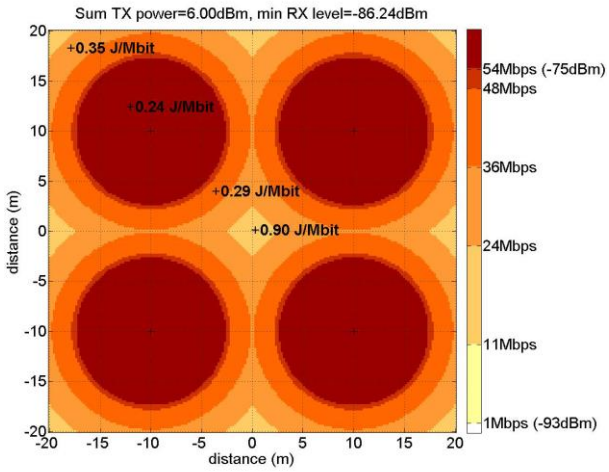

Figure 2. Map of maximum 802.11 data rate with four access points delivering a total power radiation of 6 dBm (0 dBm per distributed antenna)

In a second step, the same area is considered with four distributed access points with the same radiated power (i.e. each distributed antenna emits 0dBm of power). The simulation result is presented in Figure 2, showing a better coverage. The maximum data-rate is reachable over 43% of the total area.

These simulations show the advantages of a distributed antenna network in terms of coverage. In the following section, the energy efficiency of an 802.11 network is studied.

3. Energy efficiency in an 802.11 network

3.a. *Power measurement*

In the literature, there are few measurement reports dealing with the energy consumption of access points and terminals during a transmission when the modulation type changes. In general, device specifications showing drive current curves while transmitting and receiving are not sufficient to calculate energy consumption accurately.

In order to measure instantaneous power, we monitored the supply current of the access point and the dongle by placing a calibrated resistor in line with the power cord. The power required by the access point/dongle is the product of the voltage drop across and the current through the access point/dongle.

Power measurements were performed using a Netgear WG 602 Access point in the infrastructure mode with no encryption and a Wi-Fi USB dongle TL-WN422g from TP-Link. Other types of access points or USB dongles have been used with similar results.

The configuration of the access point enables us to choose the standard (b/g) and the modulation associated with the maximal reachable data-rate presented in the previous section. Other parameters can be freely chosen, such as fragmentation length (2346 Bytes) or RTS Threshold (2347Bytes).

Table 2 presents the power consumption during a transmission between the access point and the dongle when the modulation changes, for a fragmentation length of 2346Bytes and an RTS Threshold of 2347Bytes. The distance between the dongle and the access point was d = 1.5m. The effective throughput is measured using *Iperf* software.

Standard IEEE802.11	D (Mbit/s)	P_{AP} (W)	P_{dgl} (W)	E_b (J/Mbit)
b 1Mbps	0.8	2.71	1.06	4.7
b 11Mbps	4.8	2.47	1.18	0.76
g 24Mbps	12.7	2.48	1.24	0.29
g 36Mbps	14.8	2.42	1.24	0.25
g 48Mbps	17.5	2.38	1.25	0.21
g 54Mbps	18	2.36	1.25	0.20

Table 2. Mean power consumption (P_{AP}, P_{dgl}) and energy per bit (E_b) for different 802.11 standards during a transmission between the access point (AP) and the dongle (dgl)

Different behaviours can be distinguished, depending on the modulation scheme. For the 802.11b modulation, the mean power consumed by the access point is higher than for the best modulations owing to the reduction in packet transmission time. For the same reason the power consumed by the dongle increases with an increasing data rate. Indeed, the dongle sends acknowledgments and CTS signals more frequently. Moreover, the effective goodput measured by *Iperf* is lower than the maximum data rate given by the 802.11 standard.

3.b. Energy efficiency metric

In order to evaluate the actual energy efficiency of the Wi-Fi transmission, an appropriate metric is required to take into account the power consumption at the access point and dongle, as well as the effective throughput. For that purpose, we define the energy per bit as follows:

$$E_b = \frac{P_{AP} + P_{dgl} \quad (W)}{D \quad (Mbit/s)} \qquad \textbf{Eq. 3}$$

Where P_{AP} and P_{dgl} are the mean power consumed by the access point and the dongle respectively during a transmission, and D is the mean effective throughput measured by *Iperf*. The E_b parameter tells us how much energy the system has to spend to transmit one bit of payload data.

E_b results are shown in Figure 1 and in the last column of Table 2. The E_b value is 23.5 times higher for 802.11b (1 Mbps) than for 802.11g (54 Mbps), due to both the reduction in the overall power consumed and the increase in effective throughput.

When the distance between the access point and the mobile terminal is increased, the energy per bit increases as shown in Figure 1. To improve energy efficiency, the distance between the terminal and the access point has to be less than about ten meters for a radiated power of 6dBm. We shall therefore study in the next section the energy efficiency of a distributed antenna network by RoF, with the goal of reducing the distance between the distributed antennas and the terminals.

4. Energy efficiency of a distributed antenna system

4.a. Architecture

Figure 3 presents the architecture of a bi-directional radio-over-fibre link suitable for a fibre distributed antenna system. The signals from the access point are split electrically (not shown) to be distributed to several remote units. RF signals are adapted (ATTN) to a suitable level to directly modulate a laser diode. The resulting intensity-modulated optical carrier is transported over multimode optical fibre to a photodiode and transimpedance amplifier (TIA) to perform opto-electrical conversion. The RF signal obtained is transmitted wirelessly after a power amplifier (PA) stage. For the uplink communication, the same components are used in a symmetrical manner.

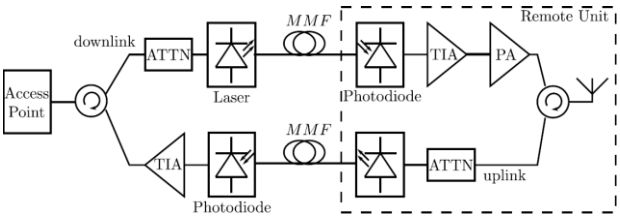

Figure 3. Generic layout of bi-directional radio-over-fibre link

In an architecture where four antennas are distributed, RF passive splitters and combiners can be used. As the loss introduced by these components prevents us from reducing the power radiated by the box, we shall consider in the following part that the consumption of the access point does not change between the centralized antenna system and the distributed antenna system.

4.b. Electrical power consumed in the optical chain

The RoF link leads to higher intrinsic power consumption, as a result of the powering/bias needed for such optoelectronic components as the laser emitter and the photodiode. At this stage, recent publications on optically powered remote units for RoF systems enable us to evaluate the (opto-)electrical power consumed in bidirectional RoF links. In [9], a 300m RoF link over multimode fiber was implemented, resulting in an amplified and radiated RF power of 8 dBm. The power consumed by the different devices is reported in Table 3. The total power consumed by a single bidirectional RoF link is 174mW, leading to an overall consumption of 696mW when four distributed antennas are considered.

Parameter	Power consumption
Laser (VCSEL)	22 mW
Photodiode	10 mW
Laser drive amplifier (ATTN)	22 mW
Transimpedance amplifier (TIA)	22 mW
Power amplifier (PA)	22 mW

Table 3. RoF link parameters [9]

4.c. Energy per bit comparison

From the electrical power consumption model of the RoF link, the total energy per bit in the whole architecture can be computed as follows, assuming that the optical power P_{opt} does not change with the modulation scheme:

$$E_b = \frac{P_{AP} + P_{dgl} + P_{opt} \quad (W)}{D \quad (Mbit/s)} \qquad \textbf{Eq. 4}$$

The energy per bit values obtained are reported in Figure 2. The mean energy per bit in the centralized antenna system is 0.72J/Mbit. This value decreases to 0.37J/Mbit for four RoF distributed antennas over the same area. Despite additional consumption by optical devices, the energy efficiency is almost twice as better in RoF DAS as in the centralized antenna system. Commercial device datasheets are used to link up the RF power received by a terminal with the 802.11 modulation scheme.

5. Conclusion

This paper shows the advantages of a distributed antenna network in terms of energy efficiency and coverage. Thanks to the measurement of power consumption of a Wi-Fi access point and USB Dongle, the energy-per-bit was evaluated as a function of the distance between the access point and a dongle. Simulations show that a distributed system with four antennas is twice more energy-efficient as a centralized antenna system. In future works the influence of the environment topography (e.g., the power decay index n) on the energy efficiency will be studied and the number of remote antennas and the corresponding radiated power has to be investigated with the knowledge of the topography.

6. Acknowlegment

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