Power Allocation for Maximizing Energy Efficiency of Mixed RF/VLC Wireless Networks

Mohamed Kashef[1], Muhammad Ismail[1], Mohamed Abdallah[1], Khalid Qaraqe[1], and Erchin Serpedin[2]

[1]Electrical and Computer Engineering, Texas A & M University at Qatar, Doha, Qatar
Email: {mohamed.kashef, m.ismail, mohamed.abdallah, khalid.qaraqe}@qatar.tamu.edu
[2]Electrical and Computer Engineering, Texas A & M University, College Station, USA
Email: serpedin@ece.tamu.edu

***Abstract*—Developing energy efficient wireless communication networks has become crucial due to the associated environmental and financial benefits. Visible light communication (VLC) has emerged as a promising candidate for achieving energy efficient wireless communication. Integrating VLC with heterogeneous wireless networks has improved the achievable data rates of mobile users. In this paper, we investigate the energy efficiency benefits of employing VLC in a heterogeneous wireless environment. We formulate the problem of power allocation for energy efficiency maximization of a heterogeneous network composed of a VLC system and a radio frequency (RF) communication system. Then, we investigate the impacts of the system parameters on the energy efficiency of the mixed RF/VLC heterogeneous network.**

I. Introduction

Energy efficient communication solutions are motivated by the increasing energy consumption of wireless networks caused by the increased demand for wireless communication services, including video streaming and data applications. The annual energy consumption of a mobile service operator is around 50-100 GWh [1]. From an environmental viewpoint, the CO_2 emissions by the telecommunication industry represent 2% of the total CO_2 emissions worldwide and are expected to reach 4% by 2020 [2].

Light emitting diodes (LEDs) have been introduced as energy efficient light sources that require approximately twenty times less power than the conventional light sources and five times less power than the fluorescent light sources [3]. Hence, replacing the current inefficient illumination sources with LEDs has the potential to reduce significantly the CO_2 emissions due to lighting. The energy saving benefits of using LEDs as a replacement for the conventional lighting sources are described in [4]. Additionally, LEDs can be used for wireless communication purposes through what is referred to as visible light communication (VLC). In VLC, communication takes place by modulating the intensity of light in such a way that it is unnoticeable to the human eyes. The receiver is a photo sensitive detector that demodulates the light signal into an electrical signal. Thus, the data transfer is performed using intensity modulation and direct detection (IM/DD) [5], which can be practically obtained by using several pulsed modulation schemes [6]. As a result, VLC can be considered as an energy efficient solution that exploits the illumination energy, which is already consumed for lighting, in data transmissions to achieve high data rates.

The energy efficiency enhancements gained as a result of using white LEDs in both illumination and communication have been discussed in [3]. Different potential applications of VLC techniques have been also introduced. The adoption of LEDs in communication using VLC techniques is reviewed in [7] where brief comparisons to different communication techniques are presented. These comparisons assume different performance criteria including energy efficiency. A more detailed comparison of the performance of VLC systems with respect to radio frequency (RF) communication systems can be found in [8].

On the other hand, heterogeneous wireless networking has been introduced to allow wireless networks with different technologies to be integrated together to enhance the overall system capacity. Such enhancements are achieved because of the diversity in fading channels, propagation losses, and the availability of resources at different networks. The resource allocation problem is a major challenge in heterogeneous networks that assume different service requirements.

Employing multiple radio interfaces at each communication terminal has proven to enhance energy efficiency in RF communication systems. In [9], the energy efficiency in an uplink communication scenario for battery-constrained mobile terminals (MTs) has been investigated. In [10], the cooperation between MTs is exploited by allowing the MTs to transmit their data efficiently to base stations using space-time coding. Also, MTs relay source data using multiple radio interfaces in [11]. Also in [12], the authors have discussed the enhancement in the energy efficiency of MTs using multi-homing capability where the MTs are allowed to aggregate the available resources from different networks.

Although VLC can attain high data rates in the presence of a line of sight (LOS) between the transmitter and the receiver, its performance degrades significantly in the absence of the LOS. Thus, reliability is a major concern for VLC systems. Also, ambient light interference is another challenge that can be mitigated by using optical filters and robust signaling schemes. On the contrary, RF wireless communication networks exhibit a higher transmission reliability even in the absence of a LOS between the transmitter and the receiver. Their main drawback

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compared to the VLC networks is that RF networks consume larger amounts of energy.

Few papers have discussed the complementary use of VLC and RF communication systems to obtain throughput and reliability benefits. In [13] and [14], the potential benefits of the VLC-RF combination and the optimal handover techniques are discussed. The hybrid use of VLC and RF systems has been discussed in [15] and [16] where the authors investigate the feasibility and potential benefits of RF/VLC hybrid systems in enhancing the throughput and increasing the coverage.

Hence, VLC and RF communication systems can work together to exploit the benefits of both systems to enhance the communication energy efficiency while maintaining good reliability. In this paper, we investigate the energy efficiency of an indoor heterogeneous network composed of a single RF access point (AP) and a single VLC AP transmitting to a number of MTs located in the coverage region of both APs. The VLC system employs its illumination power for data transmission and consumes extra data processing power. On the contrary, the RF communication system consumes both data processing and transmission powers. We formulate the problem of maximizing the heterogeneous network energy efficiency constrained by the required data rates for the MTs and the maximum allowable transmission powers for the APs. MTs are equipped with multi-homing capability and can receive data from both VLC and RF communication systems. We compare the performance of the heterogeneous network consisting of VLC and RF communication systems to the benchmarks represented by an RF only network and a heterogeneous network composed of two RF communication systems. We compare the energy efficiency of these systems numerically to quantify the effects of using mixed RF/VLC systems on the network energy efficiency.

The rest of the paper is organized as follows. The mixed RF/VLC heterogeneous network model is presented in Section II. The research problem is formulated in Section III. In Section IV, numerical results are presented. Finally, in Section V, conclusions are drawn.

II. System Model

We consider an indoor downlink scenario in which M MTs equipped with VLC receivers and RF receivers are communicating with a single RF AP and another VLC AP as shown in Fig. 1. Examples of RF wireless communication networks include cellular networks (e.g., femto-cells) and wireless local area networks (WLANs). The set of MTs is denoted by $\mathcal{M} = \{1, 2, ..., M\}$. It is assumed that all MTs are in the coverage areas of both APs. Each MT has multi-homing capability that allows simultaneous association with both networks. The multi-homing capability allows the MTs to aggregate the available resources from both networks to provide services with high performance requirements and improve network capacity [12].

The bandwidths of the VLC and the RF systems are denoted by B_{VLC} and B_{RF}, respectively. We assume that each user in the network is assigned equal fixed bandwidth allocations from

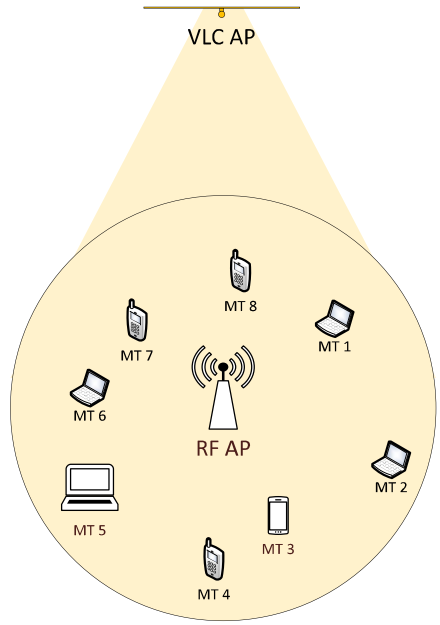

Fig. 1. System Model

the VLC and RF communication systems, given by B_{VLC}/M and B_{RF}/M, respectively. The bandwidth of the VLC system is commonly limited by the bandwidths of the LED and the photo-detector. Also, the transmission powers allocated to the mth MT by VLC and RF APs are denoted by $P_{\text{VLC},m}$ and $P_{\text{RF},m}$, respectively. The total transmitted power of an AP is constrained by the maximum allowed power which is denoted correspondingly by $P_{\text{VLC,max}}$ or $P_{\text{RF,max}}$. The fixed powers needed by the APs are denoted by Q_{VLC} and Q_{RF}. These fixed powers include the powers used for circuits operation and data processing before transmission.

The data rates achieved by the mth MT in the two networks are denoted by $R_{\text{VLC},m}$ and $R_{\text{RF},m}$, respectively, and the sum of the data rates of the mth MT is constrained to be larger than or equal to a required minimum data rate denoted $R_{\text{min},m}$.

The power gains of the channels between the mth MT and the RF and VLC APs are denoted by $G_{\text{RF},m}$ and $G_{\text{VLC},m}$, respectively. The channel power gain for the RF communication system captures both the channel fading and path loss. For the VLC system, the channel power gain captures the LOS path loss for the optical wireless signal. The distances between the APs to the mth MT are denoted by $d_{\text{RF},m}$ and $d_{\text{VLC},m}$. The thermal noise power spectral density affecting the RF receivers is denoted by $N_{0,\text{RF}}$, and it is given by $N_{0,\text{RF}} = k_{\text{B}}T$, where k_{B} stands for Boltzmann's constant and T denotes the ambient temperature. The noise power spectral density affecting the VLC receivers is dominated by the light shot noise and is denoted by $N_{0,\text{VLC}}$. The characteristics of the channel models can be found in [8].

The RF communication path loss typically takes the form

$$\text{PL[dB]} = A\log_{10}\left(d_{\text{RF},m}[m]\right) + B + C\log_{10}\left(\frac{f_c}{5}\right) + X, \quad (1)$$

where f_c is the carrier frequency in GHz, A, B and C

are constants depending on the propagation model, and X stands for an environment specific term. For the LOS scenario, $A = 18.7$, $B = 46.8$ and $C = 20$. For the non-LOS (NLOS) scenario, $A = 36.8$, $B = 43.8$, $C = 20$ and $X = 5(n_w - 1)$ in case of light walls or $X = 12(n_w - 1)$ in case of heavy walls where n_w denotes the number of walls between the AP and the MT. Hence, the channel power gain is defined as

$$G_{\text{RF},m} = 10^{-\text{PL[dB]}/10}. \tag{2}$$

We denote the channel power gain in the presence of LOS by $G^{\text{LOS}}_{\text{RF},m}$ and for the NLOS scenarios by $G^{\text{NLOS}}_{\text{RF},m}$. For VLC systems, the channel power gain is given in [8] by

$$G_{\text{VLC},m} = \frac{(n+1)\cos^n(\phi_{ij})A_j\cos(\theta_{ij})}{2\pi d^2_{\text{VLC},m}}, \tag{3}$$

where A_j stands for the physical area of the photo detector, ϕ_{ij} denotes the angle of irradiance from the corresponding LED, n is the order of the Lambertian emission defined by the LED's semi-angle at half power Φ, which is $n = \ln(1/2)/\ln(\cos(\Phi))$, and θ_{ij} represents the angle of incidence.

The LOS availability probabilities for RF and VLC systems are defined as the probability that there are no obstacles in the communication link between the MT and the corresponding AP, which are denoted by ρ_{RF} and ρ_{VLC}, respectively. In the case of RF transmissions, the channel path loss exponent increases with the LOS absence as discussed earlier. For the case of VLC, the signal is degraded significantly in the absence of LOS that may result in unsuccessful data transmissions. In this work, we assume that NLOS VLC transmissions are unsuccessful.

III. Energy Efficiency Maximization

In this section, we formulate the energy efficiency maximization problem. Energy efficiency is defined as the total achieved data rate per unit power consumption. The heterogeneous network energy efficiency is defined as the summation of the individual networks energy efficiencies.

The average received signal to noise ratios for the mth MT from the RF and VLC systems are denoted by $\gamma_{\text{RF},m}$ and $\gamma_{\text{VLC},m}$, respectively, and can be expressed as in [8]

$$\gamma_{\text{RF},m} = \frac{P_{\text{RF},m}G_{\text{RF},m}}{(B_{\text{RF}}/M)N_{0,\text{RF}}} \tag{4}$$

$$\gamma_{\text{VLC},m} = \frac{(\rho P_{\text{VLC},m}G_{\text{VLC},m})^2}{(B_{\text{VLC}}/M)N_{0,\text{VLC}}}. \tag{5}$$

where ρ stands for the responsivity of the used photodetector, and the value of $G_{\text{RF},m}$ can be substituted by $G^{\text{LOS}}_{\text{RF},m}$ or $G^{\text{NLOS}}_{\text{RF},m}$ to obtain the corresponding $\gamma^{\text{LOS}}_{\text{RF},m}$ and $\gamma^{\text{NLOS}}_{\text{RF},m}$ for the LOS and NLOS channels.

The data rates achieved by the mth MT via VLC and RF transmissions are denoted by $R_{\text{VLC},m}$ and $R_{\text{RF},m}$, respectively. Using the multi-homing capability, the sum of the achievable data rates of the mth MT via the VLC and RF APs should not be less than the required data rate $R_{\text{min},m}$. The expected values of the achievable data rates from each AP are averaged over the probability mass function of LOS availability and are expressed as follows

$$R_{\text{RF},m} = \frac{B_{\text{RF}}}{M}\left(\rho_{\text{RF}}\log_2\left(1+\gamma^{\text{LOS}}_{\text{RF},m}\right) + (1-\rho_{\text{RF}})\log_2\left(1+\gamma^{\text{NLOS}}_{\text{RF},m}\right)\right) \tag{6}$$

$$R_{\text{VLC},m} = \frac{B_{\text{VLC}}}{M}\rho_{\text{VLC}}\log_2\left(1+\gamma_{\text{VLC},m}\right). \tag{7}$$

The energy efficiencies of VLC and RF communication systems are denoted by η_{VLC} and η_{RF}, respectively. The energy efficiency for the VLC AP is calculated using the fact that the transmission power is an optical power which is used for illumination by design, and hence only the fixed power consumption Q_{VLC} is accounted for as a power cost. Hence, η_{VLC} can be expressed as

$$\eta_{\text{VLC}} = \frac{\sum_{m\in\mathcal{M}} R_{\text{VLC},m}}{Q_{\text{VLC}}}. \tag{8}$$

On the other hand, the RF power consumption accounts for both processing and transmission powers, and hence, η_{RF} is expressed as

$$\eta_{\text{RF}} = \frac{\sum_{m\in\mathcal{M}} R_{\text{RF},m}}{Q_{\text{RF}} + \sum_{m\in\mathcal{M}} P_{\text{RF},m}}. \tag{9}$$

We study the power allocation problem to maximize the energy efficiency of the heterogeneous network in terms of the assigned powers to the MTs by the APs. The users total achieved data rates, i.e., $R_{\text{VLC},m} + R_{\text{RF},m}$ are constrained by the minimum required data rates for the MTs. For each AP, the total transmission power consumption, i.e., $\sum_{m\in\mathcal{M}} P_{\text{VLC},m}$ or $\sum_{m\in\mathcal{M}} P_{\text{RF},m}$, is constrained by the maximum allowable transmission power. Given these constraints, the problem is formulated as follows:

$$\begin{aligned}
&\max_{P_{\text{VLC},m},P_{\text{RF},m}} \; \eta_{\text{VLC}} + \eta_{\text{RF}} \\
\text{s.t.} \quad & R_{\text{VLC},m} + R_{\text{RF},m} \geq R_{\text{min},m}, \quad \forall m \in \mathcal{M}, \\
& \sum_{m\in\mathcal{M}} P_{\text{VLC},m} \leq P_{\text{VLC,max}}, \\
& \sum_{m\in\mathcal{M}} P_{\text{RF},m} \leq P_{\text{RF,max}}, \\
& P_{\text{VLC},m}, P_{\text{RF},m} \geq 0, \quad \forall m \in \mathcal{M}.
\end{aligned} \tag{10}$$

Based on the VLC energy efficiency definition (8), we observe that maximizing the energy efficiency requires the VLC system to exploit the maximum allowable transmission power as the rate function is monotonically increasing in the transmission power which does not appear in the denominator of the VLC energy efficiency function since we do not pay extra penalty for this power which is already exploited in illumination. In this work, the problem is solved numerically to gain insights about the energy efficiency benefits offered by VLC in designing heterogeneous networks that assume RF communications as well. A further study is needed to obtain a more computationally efficient technique to solve this resource allocation problem, which is outside the scope of this paper and will be treated in an upcoming accompanying paper.

IV. Numerical Results

In the following, we assess the performance of the proposed power allocation problem. We compare the energy efficiency of the proposed mixed RF/VLC heterogeneous network to two benchmark systems. We will refer to the proposed system in the following results by 'RF-VLC'. We compare it to a system consisting of a single RF wireless network, which is denoted by 'RF-Only', and hence no multi-homing is assumed, and we also compare it to a system comprising two RF APs with different frequency bands and which will be denoted by 'RF-RF', and hence multi-homing is achieved only over RF links. In the system with two RF APs, one of the RF systems is assigned a bandwidth equal to that of the VLC system to ensure a fair comparison.

In the following simulations, we set the parameters as follows except otherwise stated. We set $R_{\min,m} = 2$ Mbps, $P_{\text{RF,max}} = 1$ watt, $Q_{\text{RF,max}} = 6.7$ watts, $Q_{\text{VLC,max}} = 6$ watts, $N_{0,\text{RF}} = 3.89\text{x}10^{-21}$ watts/Hz, $N_{0,\text{VLC}} = 10^{-21}$ watts/Hz, $B_{\text{RF}} = 5$ MHz, $B_{\text{VLC}} = 10$ MHz, $\rho = 0.3$ and $M = 7$. Both the RF and VLC APs are located at the same position with MTs located in a circle with a distance to the APs of 1.5 meters. The VLC system maximum power is the product of the number of LEDs used at the VLC source with the maximum power of each LED. We set the number of LEDs to be 38 with the maximum power of a LED to be 189 milli-watts. The values of the VLC and RF systems are obtained from [8] and [17], respectively.

In Fig. 2, we show the energy efficiency of the different systems against the number of MTs. The performance of the RF-VLC system is significantly better than the performance of the RF-only system because of the multi-homing capability of the MTs and the energy efficiency of the VLC systems. Also, the performance of the RF-VLC is better than that of the RF-RF because of the low VLC AP power consumption compared to the RF communication systems.

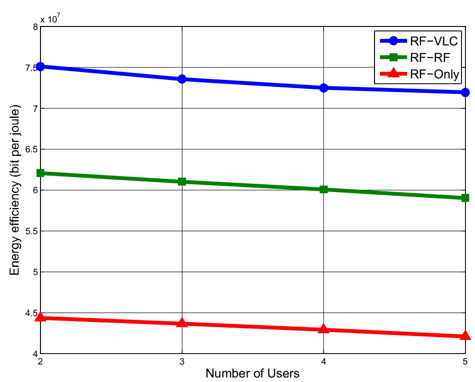

Fig. 2. Energy efficiency against the number of MTs.

In Fig. 3, we show the energy efficiency performance versus the fixed power consumption of the VLC AP. The energy efficiencies of the RF APs are independent of the fixed power of VLC system. The energy efficiency of RF-VLC can approach the efficiency of the RF-RF system when the fixed power is 9 watts which is nearly 1.5 times the fixed power of an RF AP. Consequently, the integration of a VLC system in a heterogeneous networking with RF communication will not be beneficial if the VLC AP fixed power is notably high compared to an equivalent RF AP.

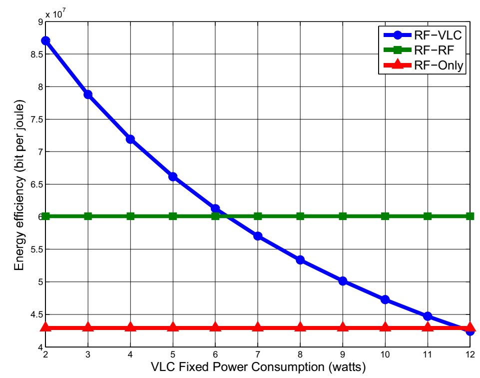

Fig. 3. Energy efficiency against the fixed power of the VLC system.

We study in Fig. 4 the effect of the number of LEDs on the energy efficiency of the RF-VLC system. Increasing the number of LEDs allows higher transmission power for the VLC system which motivates the MTs to obtain most of their required data service from the VLC AP, reducing the transmission power consumption of RF AP, and hence improving the overall energy efficiency.

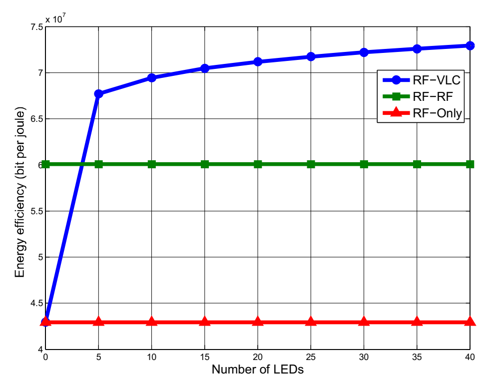

Fig. 4. Energy efficiency against the number of LEDs used by the VLC system.

In Fig. 5, we consider the case in which the LOS availability probabilities for RF and VLC systems are equal. We show the energy efficiency versus the LOS availability probability. The performance for the RF-VLC system is better than the benchmarks when the probability of the LOS for the VLC is higher than 0.5 because of the good energy efficiency properties for the proposed RF-VLC system. Also, the slope of the curve of the RF-VLC energy efficiency is higher than that of the benchmark systems because of the significance of the LOS availability in the VLC system compared to the RF systems.

Finally, we discuss the effect of LOS availability probability in the RF system on the energy efficiency of the RF-VLC

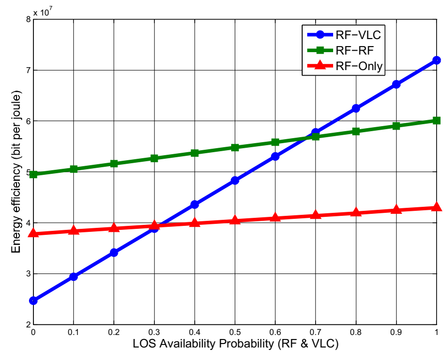

Fig. 5. Energy efficiency against the LOS availability probability for VLC and RF systems.

heterogeneous system when $\rho_{\text{VLC}} = 0.5$. In the RF-VLC system, the users exploit the less costly VLC energy in data transmission and exploit the RF transmission power when required. Therefore, the enhancement of the performance with the increase of LOS availability probability presents a smaller slope than those associated with RF systems. Thus, positioning the VLC AP to improve the LOS availability probability is more beneficial to the system than enhancing the LOS availability probability for the RF system.

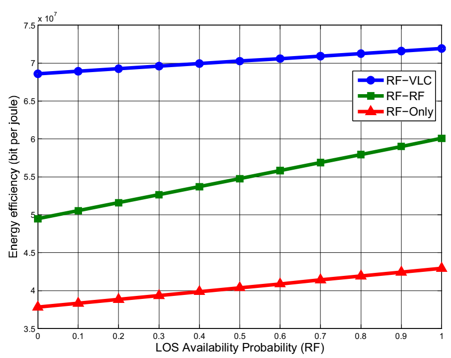

Fig. 6. Energy efficiency against the LOS availability probability of the RF systems.

V. Conclusions

The research in the area of energy efficient communications has been motivated by different environmental and financial considerations. Integrating VLC and RF APs in heterogeneous wireless networks has shown promising improvements in terms of energy efficiency. Hence, employing VLC in heterogeneous networks enhances energy efficiency. The multi-homing capability of the MTs in a heterogeneous network with VLC and RF APs allows users to benefit from the huge unlicensed bandwidth of the visible light spectrum and the low cost of the transmission power. It also allows for improved reliability, as RF communications are employed in absence of VLC LOS. We have shown the superior performance of a heterogeneous network consisting of VLC and RF relative to the benchmarks of an RF network only and a heterogeneous network that consists of two RF systems. We also have investigated the effect of the LOS availability probabilities for both systems. We have shown that VLC system performance depends heavily on LOS availability in the sense that network performance degrades significantly in the absence of LOS for the VLC system.

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