Efficiency of Opportunistic Cellular/LiFi Traffic Offloading

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Abstract
Data offloading efficiency in a cellular/light fidelity network is investigated. This offloading efficiency is a measure of the ratio of traffic carried by light fidelity (LiFi) network to total traffic carried by both LiFi and cellular networks. The effect of LiFi-signal blocking and channel characteristics are considered. Different LiFi offloading timing cases are discussed. Simulation is performed in order to explore the performance of opportunistic cellular/LiFi traffic offloading scenario. Simulation results reveal that LiFi-signal blocking can reduce the offloading efficiency by more than 30%.

Keywords: Cellular network, HetNet, LiFi, LTE, offloading, visible-light communication (VLC).

1. Introduction

Over the last 5 years, mobile data traffic has grown up to 18−fold. Cisco announced that global mobile traffic grew about 63% in 2016 and it will increase by 7−fold from 2016 to 2021 [1]. To cope with this huge capacity requirements, the cellular networks operators attempt to find suitable, cost-effective, and power-saving solutions to carry the expected huge amount of data traffic. Upgrading existing cellular networks, by increasing the number of base-stations or making the cell smaller, would increase both capital expenditure (CAPEX) and operation expense (OPEX) [2]. Offloading provides a promising cost-effective window to deal with the increasing traffic demand of the next generation cellular mobile networks [3]. WiFi and mmWave technologies are efficient offloading solutions for the data traffic of cellular networks [2, 4].

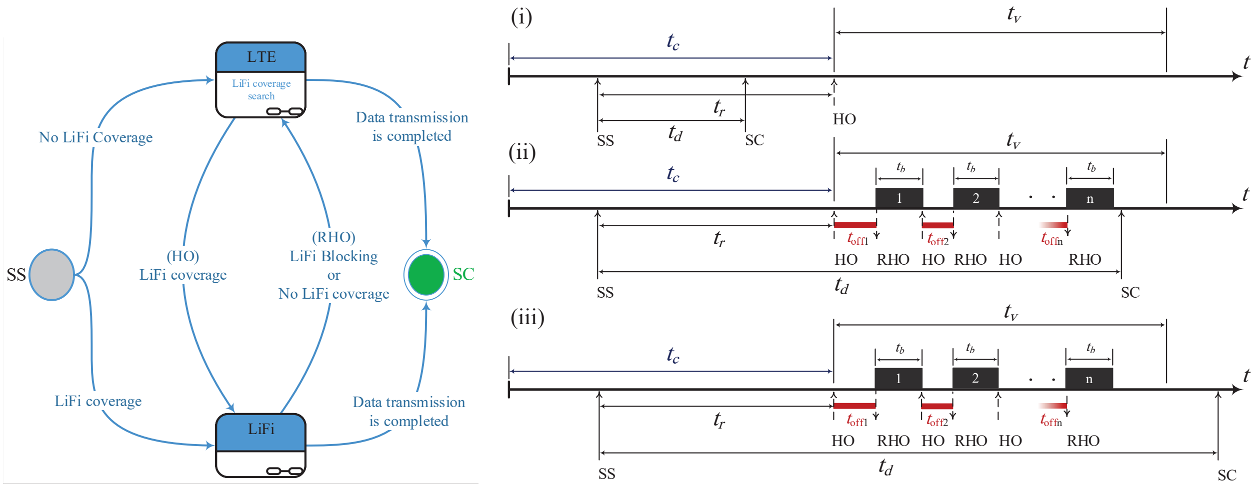
Researchers from academia and experts from industry have given a considerable attention to the visible light communication (VLC) as a possible alternative that can fulfill the need of higher capacity beyond the capabilities of radio frequency (RF) communication [5]. Furthermore, VLC systems have several advantages compared to RF systems such as: lack of light usage regulations (no need for license), less health side effects of VLC transmitted power, more secure connection [6]. Haas *et al.* have introduced the light fidelity (LiFi) attocells as a new tier in heterogeneous networks (HetNet). Unlike point-to-point VLC communication, LiFi provides multipoint communication, and is considered as a complete wireless optical network. Furthermore, LiFi guarantees user equipment (UE) mobility that is essential for proper operation of HetNet [5].

The offloading efficiency of cellular/WiFi HeNet has been discussed in [7]. However, the efficiency of using LiFi to offload traffic from a cellular network has not been investigated yet. In this paper, our main aim is to discuss the traffic offloading efficiency of opportunistic cellular/LiFi HetNet. In addition, the effect of LiFi-signal blocking is taken into consideration. Furthermore, the effects of user existence in LiFi cell and dynamic variation of user densities on LiFi offloading efficiency are considered.

The rest of this paper is organized as follows. In Section 2, state- and timing-diagram for different offloading cases are explained and mathematical expressions for the distributions of different timing parameters are given. In Section 3, the LiFi offloading efficiency is investigated numerically. Finally, the conclusions are given in Section 4.

2. LiFi Offloading Analysis

The state diagram that indicates the operations implemented during opportunistic cellular/LiFi offloading is shown in Fig. 1a. We assume that user is covered by the cellular network all the time, and the user can be managed by both cellular and LiFi cells. When the session starts (SS), the UE checks



(a) (b)

Fig. 1. (a) State-diagram framework for traffic offloading of opportunistic cellular/LiFi HetNet; SS: session start and attempt, SC: session complete, HO: vertical handover from cellular to LiFi cells, and RHO: reverse vertical handover from LiFi to cellular cells. (b) Timing diagrams of LiFi offloading for different cases: (i) $t_d < t_r$, (ii) $t_r \le t_d < t_r + t_v$, and (iii) $t_d \ge t_r + t_v$.

whether it is covered by a LiFi network or not. If there is an available LiFi access point (AP), the UE will be served by this LiFi AP. Otherwise, the UE will be served by the RF cellular network. During data transmission through cellular network, the UE keeps searching for LiFi coverage. If LiFi coverage is found, UE will connect to the new LiFi AP. Under LiFi connection, if the LiFi-signal level becomes lower than a threshold level, a reverse vertical handover (RHO) from LiFi to cellular network will take place.

Fig. 1b shows different timing cases for cellular/LiFi offloading. The average LiFi offloading times can be calculated from the average of three distinct cases:

1 When $t_d < t_r$, as shown in Fig. 1b(i), no traffic is offloaded to LiFi network and $\mathrm{E}\{\sum t_{\text{off}}\} = 0$, with $\mathrm{E}(\cdot)$ denoting the expectation operator.

2 When $t_r \le t_d < t_r + t_v$, as shown in Fig. 1b(ii), the expectation of offloading time is given by $\mathrm{E}\{\sum t_{\text{off}}\} = \mathrm{E}\{t_d - t_r - \sum t_b\}$.

3 When $t_d \ge t_r + t_v$, as shown in Fig. 1b(iii), the expectation of offloading time is given by $\mathrm{E}\{\sum t_{\text{off}}\} = \mathrm{E}\{t_v - \sum t_b\}$.

Different timing parameters can be modeled by statistical distributions. The cellular residence time (t_c) follows a general distribution with mean μ_c^{-1} [8]. We consider exponential distribution with mean (μ_c^{-1}) to describe t_c with probability density function (pdf) $f_{t_c}(t_c;\mu_c)$ and cumulative distribution function (CDF) $F_{t_c}(t_c;\mu_c)$ given as:

$$f_{t_c}(t_c;\mu_c) = \mu_c \exp(-\mu_c t_c), \tag{1}$$

$$F_{t_c}(t_c;\mu_c) = 1 - \exp(-\mu_c t_c). \tag{2}$$

Considering user-centric LiFi network, once a user finds LiFi coverage he will stay a long time inside it. Based on that scenario, LiFi residence time (t_v) can be characterized by a two-stage hyper-exponential distribution with mean μ_v^{-1}. The corresponding pdf and CDF are given as [7, 8]:

$$f_{t_v}(t_v;\mu_v) = \frac{a^2}{a+1}\mu_v \exp(-a\mu_v t_v) + \frac{a}{a+1}\mu_v \exp\left(-\frac{\mu_v}{a}t_v\right), \tag{3}$$

$$F_{t_v}(t_v;\mu_v) = 1 - \frac{a}{a+1}\exp(-a\mu_v t_v) + \frac{1}{a+1}\exp\left(-\frac{\mu_v}{a}t_v\right), \tag{4}$$

respectively, where a is a variability parameter that affects the skewness of t_v. Increasing a, $f_{t_v}(t_v;\mu_v)$ will be more skewed to the left with a longer tail, i.e., increasing the probability of shorter LiFi residence time [7]. The session time (t_d) follows an exponential distribution with mean μ_d^{-1}. The corresponding pdf and CDF are given as:

$$f_{t_d}(t_d;\mu_d) = \mu_d \exp(-\mu_d t_d), \tag{5}$$

$$F_{t_d}(t_d;\mu_d) = 1 - \exp(-\mu_d t_d). \tag{6}$$

Based on the residual life theorem [7], the pdf of elapsed time from session start to the first handover (t_r) is defined as $f_{t_r}(t_r) = \mu_c(1 - F_{t_c}(t_c;\mu_c))$. Considering an exponential distribution of t_c, t_r is exponential too with mean μ_c^{-1}. Its pdf and CDF are given as follows [7]:

$$f_{t_r}(t_r;\mu_c) = \mu_c \exp(-\mu_c t_r), \tag{7}$$
$$F_{t_r}(t_r;\mu_c) = 1 - \exp(-\mu_c t_r). \tag{8}$$

The blocking time (t_b) is the time during which a user is covered by LiFi-AP but receiving power levels less than specific threshold, Γ_{TH}. Thus t_b is well described by a joint independent probability as follows:

$$\begin{aligned} f_{t_b}(t_b) &= P_r(P < \Gamma_{\mathrm{TH}}) \left[\frac{a^2}{a+1}\mu_v \exp(-a\mu_v t_b) + \frac{a}{a+1}\mu_v \exp\left(-\frac{\mu_v}{a}t_b\right) \right] \\ &= \left[1 - \exp\left(-\frac{\Gamma_{\mathrm{TH}}}{2\sigma^2}\right) \right] \left[\frac{a^2}{a+1}\mu_v \exp(-a\mu_v t_b) + \frac{a}{a+1}\mu_v \exp\left(-\frac{\mu_v}{a}t_b\right) \right] \end{aligned} \tag{9}$$

The above t_b pdf is derive based on considering that the normalized received LiFi-signal power follows a Rayleigh distribution with a scale parameter (σ) that is related to users' density within the LiFi cell [9, 10].

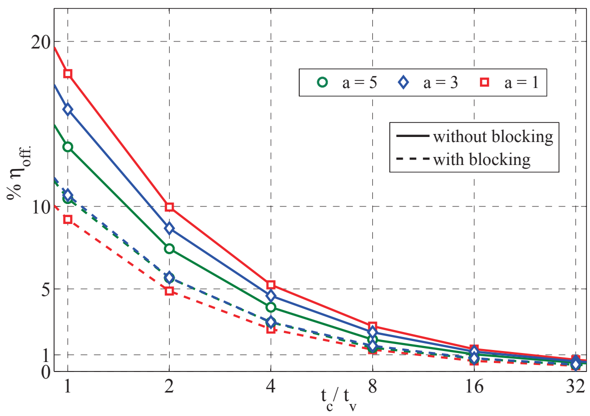
The offloading efficiency is defined as the ratio of the traffic that can be carried over a LiFi network to the total traffic over cellular/LiFi HetNet; it can be expressed as:

$$\eta_{\mathrm{off.}} = \frac{r_v \mathrm{E}\{\sum t_{\mathrm{off}}\}}{r_v \mathrm{E}\{\sum t_{\mathrm{off}}\} + r_c\left(\mathrm{E}\{t_d\} - \mathrm{E}\{\sum t_{\mathrm{off}}\}\right)}, \tag{10}$$

where r_v and r_c are the data rate over LiFi and cellular networks, respectively.

3. Results and Discussion

The simulation scenario is based on event-driven simulation, where random values are generated to all t_r, t_v, t_d, and t_b based on their distributions. Using these random values and based on state- and timing-diagram in Fig. 1, the average offloading efficiency is calculated. In our simulation, we use the following parameters values $\mu_v = 100$, $\mu_d = \mu_v/10$, and ratio of LiFi data rate to cellular data rate follows nominal offloading rates $r_v : r_c = 5:2$ [11]. The threshold minimum power, Γ_{TH}, is assumed to be 50% of the LiFi transmitted power.



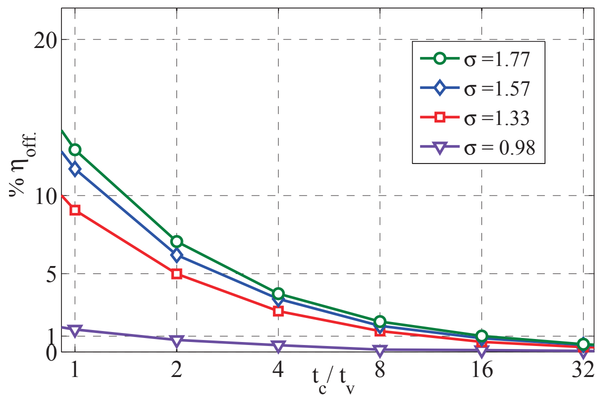


Fig. 2. Offloading efficiency for cellular/LiFi HetNet versus the ratio t_c/t_v at: (a) different values of variability parameter ($a = 1,\ 3$, and, 5) with and without LiFi blocking consideration; (b) different level of users' density of $\sigma = 1.77,\ 1.33,\ 1.57$, and 0.98, at a variability parameter of $a = 1$, taking LiFi signal blocking into consideration.

The effects of both LiFi blocking and variability parameter a are illustrated in Fig. 2a. The offloading efficiency is shown versus the mean of cellular residence time normalized by the mean of LiFi residence time considering the two cases of blocking and non-blocking at different values of variability parameter ($a = 1,\ 3$, and 5) and at scale parameter value of $\sigma = 1.33$. It is clear that LiFi signal blocking reduces the amount of offloaded traffic from cellular network by more than 30%. Concerning the effect of changing the variability parameter (a) for non-blocking case, as a increases the offloading efficiency decreases. This can be explained as increasing a leads to more skewing towards the left with a longer tail of the distribution. This means that a smaller LiFi residence time, which results in most of the traffic carried by the cellular network. In case of LiFi-signal blocking, the effect of changing a is reversed. It can be explained as follows. Reducing a results in less skewing towards the left with a shorter tail of the distribution. This means that a higher LiFi residence time. Consequently, this leads to higher probability of LiFi-signal blocking and the overall offloading efficiency is reduced.

Figure 2b illustrates the effect of users' density within the LiFi cell on the offloading efficiency. The offloading efficiency is drawn versus the mean of cellular residence time normalized by the mean of LiFi residence time at different values of scale parameter (σ). These values correspond to different users' densities inside LiFi cell as follows: at high users' density of $1.11\ \text{users}/\text{m}^2$ the scale parameter $\sigma = 1.77$, while for empty room the scale parameter $\sigma = 0.98$. These values of σ are based on experimental results, in [9], that used four light sources with no reflection from walls. It is found that, by increasing the users' density, the reflections of LiFi-signal on them will contribute and increase the received LiFi power; that leads to a reduction in the outage probability. Hence, the blocking probability will be reduced, and consequently the offloading efficiency will be increased.

4. Conclusion

We have investigated traffic offloading efficiency of cellular/LiFi HetNet. A framework of opportunistic cellular/LiFi offloading and timing diagrams for different disjoint cases have been illustrated. Statistical distributions for different times have been explored. Our results reveal that LiFi blocking reduces the traffic offloading efficiency. In addition, the users' density has a positive effect on LiFi offloading efficiency in opportunistic cellular/LiFi HetNet.

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