An Approximation of the Backhaul Bandwidth Aggregation Potential Using a Partial Sharing Scheme

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***Abstract*—To cope with the increasing demands of mobile devices and the limited capacity of cellular networks, mobile connections are offloaded to WiFi. The access capacity is further increased by aggregating backhaul bandwidth of WiFi access links. To analyze the performance of aggregated access links we develop a model for two and more cooperating systems sharing capacities using an offloading scheme. The state probabilities of the different cooperating systems in the analytic model are determined by a fixed point iterative procedure. By investigating an inner and outer composite system we are able to analyze the system in imbalanced load conditions where the system reaches its full potential utilizing spare bandwidth. To evaluate the robustness of the system against users that try to exploit the system, the bandwidth received by prioritized users is quantified.**

***Keywords*-Markov Model; Partial Sharing; Bandwidth Aggregation; WiFi; Fairness**

I. Introduction

In 2015, mobile networks carried more than 40 exabytes of traffic, which is expected to increase 8-fold towards 2020 [1]. To handle the growth and to reduce the load on mobile networks, offloading to WiFi has come to the center of industry thinking [2].

In contrast to strict offloading, in which the Internet access link is switched completely, e.g., from cellular to WiFi, current concepts such as BeWifi[1] also consider multiple connections to the Internet, thereby sharing and aggregating available backhaul access link capacities. The question is which sharing policy to apply for which system characteristics. In the case of BeWifi, which considers access link sharing among neighboring users, each user should only share its access link when having spare capacity in order to avoid negatively affecting his own Internet connections. Therefore, two thresholds were introduced, i) a support threshold until which utilization a user will offer bandwidth to other users, and ii) an offloading threshold indicating from which utilization a user can offload to supporting neighbors. It is hard and non-intuitive to determine the threshold settings for fair and effective operation of a bandwidth sharing system. In this work a partial bandwidth sharing environment with offloading policy is investigated using an analytic model. A direct application of the model is the aggregation of backhaul bandwidth by connecting neighboring access links.

In [3] a Markov model has been developed to analyze the bandwidth aggregation potential of two neighboring access links. In urban environments there are far more than two access links available. Telefonica is also aiming to use BeWifi in densely populated areas. It is shown in pilot studies that the technology's only limitation is the actual WiFi bandwidth available. In densely populated areas bandwidth of a high number of WiFi access points is aggregated. As shown in [4], an average of 25 WiFi access points are visible in every scan in densely populated areas. In this case an assessment with the model previously proposed by the authors is not possible, since it is limited to two access links only. An extension of the existing model to m dimensions would require solving an equation system with n^m equations, which is computationally too complex. Therefore the proposed approximation is necessary. We extend the Markov model to be applicable for two and more links using a fixed point approximation. This allows us to reduce the n-dimensional Markov chain to evaluate the steady state probabilities efficiently.

The contribution of this paper is three-fold. First, the approximation using fixed point iteration can be used to seamlessly evaluate the performance of systems between partitioning and complete sharing dependent on the threshold settings. Second, by considering an outer and an inner composite system we are able to apply the method to the case of heterogeneous load, which is crucial to assess the full potential of the approach. Bandwidth sharing systems are designed to increase the throughput of systems that are currently overloaded by using spare bandwidth of underutilized links. In such situations the load on the links is highly heterogeneous. Our results show that an overloaded system can highly benefit, by receiving multiples of its own capacity, from spare bandwidth of underutilized cooperating systems. Third, we evaluate the robustness of the mechanism against free riders by prioritizing links and find that altruistic users may only lose slightly more bandwidth than in normal operation. This is important, since a bandwidth sharing system that is running an inefficient offloading policy may be exploited by free riders that claim spare bandwidth by offloading traffic, but do not share any of their own bandwidth.

[1] http://www.tid.es/research/areas/bewifi

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The paper is structured as follows. Section II summarizes offloading and bandwidth sharing systems and technologies. In Section III, the model of a bandwidth aggregation system is described in detail. Results of the performance evaluation are reported in Section IV, while Section V lays out the conclusions derived from the entire study.

II. Background and Related Work

The principle of sharing or offloading between multiple Internet access links is already widely used by commercial services as well as research work. WiFi-sharing communities like Fon[2], Karma[3], WeFi[4], and Boingo[5] offer access to an alternative Internet link (WiFi instead of mobile), which provides a faster access bandwidth and reduces the load on stressed mobile networks. With respect to this so called WiFi offloading, the research community investigated incentives and algorithms for access sharing [5], and ubiquitous WiFi access architectures for deployment in metropolitan areas [6], [7]. Moreover, [8], [9], [10] describe systems for trust-based WiFi password sharing via an online social network (OSN) app. WiFi sharing is not a legal vacuum and a first exemplary overview on Swiss and French rights and obligations was given in [11] but must be treated with caution due to international differences and interim law revisions. The opposite concept to Wifi offloading, i.e., WiFi onloading, is presented in [12]. The idea is to utilize different peaks in mobile and fixed networks to onload data to the mobile network to support applications on short time scales (e.g., prebuffering of videos, asymmetric data uploads).

An access link sharing concept, which goes beyond pure offloading, is BeWifi, which was developed by Telefonica [13] and builds on previous works about backhaul capacity aggregation [14], [15]. BeWifi uses modified access points, which act as normal access points until their clients saturate more than 80% of the backhaul capacity. Then, the access point will scan for close access points, which will provide additional bandwidth if their utilization is below 70%. Backhaul capacity and utilization are announced by each access point via beacon frames. Instead of introducing a secondary WiFi radio, BeWifi uses time-division multiple access (TDMA) and the 802.11 network allocation vector (NAV) to connect to neighboring access points for bandwidth aggregation in a round robin fashion with a weighted proportional fairness schedule.

From a technical perspective, bandwidth sharing and offloading are enabled by implementing handovers and/or multipath connections, which are well covered in research. [16], [17], [18] show the feasibility of multipath TCP for handovers between mobile and WiFi networks in the current Internet and [19] describes available features for mobile traffic offloading. Futhermore, [20] gives an overview on approaches that enable mobility and multihoming. In opposition to existing (free) WiFi sharing approaches, an authentication (at the provider / within the wireless home network) is required for bandwidth aggregation approaches. This may reduce legal complexity and thus simplify the deployment of the systems.

Theoretically, bandwidth sharing between WiFi access points can be considered as load sharing among systems. Generally load sharing systems can be classified in partitioning, partial sharing and complete sharing systems. Partitioning systems work completely independent from each other. Each system has its own queue and buffer space and processes only requests arriving at its queue. Complete sharing systems have a shared queue and buffer space. When processed, a request in the shared queue is assigned to the system which is currently least loaded. Partial sharing systems have their own queues, but may offload requests to other systems if they are overloaded, or process requests from other overloaded systems. Different partial sharing or complete sharing models have been investigated in literature. In [21] the bandwidth usage by different services in a broadband system in complete sharing and partial sharing mode with trunk reservation is investigated. Multidimensional Markov chains are used in [22], [23], [24] to evaluate the performance of cellular network systems with different service categories. The blocking probability of a complete sharing system has been approximated in [25]. This approximation is used in [26] to evaluate the performance of mobile networks with code division multiplexing supporting elastic services. However, none of the models can be used to seamlessly evaluate the performance of systems between partitioning and complete sharing. Thus, in [3], a model was developed based on a two dimensional Markov chain with thresholds to study the transition of blocking probabilities of partitioned, partial sharing, and complete sharing systems. The thresholds determine the load on a link, above which it tries to offload to other less utilized links. If the thresholds are set to zero, the system corresponds to a complete sharing system. If the thresholds are set to the link capacity, offloading is not possible, which corresponds to partitioned systems. As shown above, the Markov model is limited to two access links only. This limits its applicability, since the number of average WiFi access points visible to clients is much higher in densely-populated areas. Therefore, we extend the model to be applicable to multiple access links by utilizing a fixed point approach. The fixed point approximation is used to reduce the n-dimensional Markov chain to one dimension similar to [27], [28] where the approach is used for analytic models for polling systems and the interference distribution in UMTS networks, respectively. The underlying Markov chain highly differs from existing fix-point approaches, since it considers support and offloading thresholds. To the best

[2] http://www.fon.com
[3] https://yourkarma.com/
[4] http://wefi.com/
[5] http://www.boingo.com/

of our knowledge this is also the first work that considers an inner and an outer composite system to apply the fixed point analysis in heterogeneous load conditions.

III. Model and Analysis

In the following, we first describe the system model and the considered scenario in detail, covering the notation used for parameters throughout this work. We present analytic approaches that are used to derive the resulting performance metrics, like blocking probability and received bandwidth.

A. General Model

For simplicity and mathematical tractability we make assumptions on the link capacities and the service rates of bandwidth fractions. This allows analytic performance evaluation of bandwidth aggregation systems with offloading policy and understanding its characteristics.

Assumption 1: The switching time to another access link is zero.

In practice, TDMA is used to aggregate the bandwidth of two access points operating on different channels. The system utilizes inband signaling and a switching frequency of 1/10s, such that no concurrent data transmission via different frequencies is taking place. Hence, the impact on the battery consumption should be negligible. During the time in which the client is switching frequencies, it cannot send or transmit data. This time is called switching time and for state of the art systems it is 1.5ms [13]. This switching time slightly decreases the effective throughput of the system. Signaling among the cooperating access points is necessary to report the current load and the offloading state. The messages exchanged produce a signaling overhead, which can limit the performance of the system. In practice APs announce their backhaul link capacity through Beacon frames, as well as their available-for-aggregation throughput, i.e. the part of their capacity that is not utilized by their clients [13]. However, in [13] the aggregate throughput remains almost constant across the different experiments, indicating that the overhead of switching and signaling is fixed and only slightly impacts the overall throughput.

Assumption 2: The wireless channels are clean.

Interference can limit the capacity of the wireless links. The effect of the channel quality on the aggregation capacity is evaluated in [13]. To account for a bad channel quality in our model, the link capacity can be reduced accordingly.

Assumption 3: The service time of bandwidth fractions follows a negative exponential distribution.

We follow up the methodology for two access links described in [3], and model the load on $m \geq 2$ access links as depicted in Figure 1. The throughput of each Internet connection is limited by a bottleneck (either on application side, on server side, or in the core Internet), such that single connections will utilize a certain share of the access link bandwidth. Therefore, the available capacity of a link c is divided into a number n of small atomic bandwidth fractions of equal size. This means, $c = n \cdot \xi$ with a global constant ξ denoting the granularity of bandwidth allocation. Thus, different capacities c_i are modeled by assigning different n_i to the links.

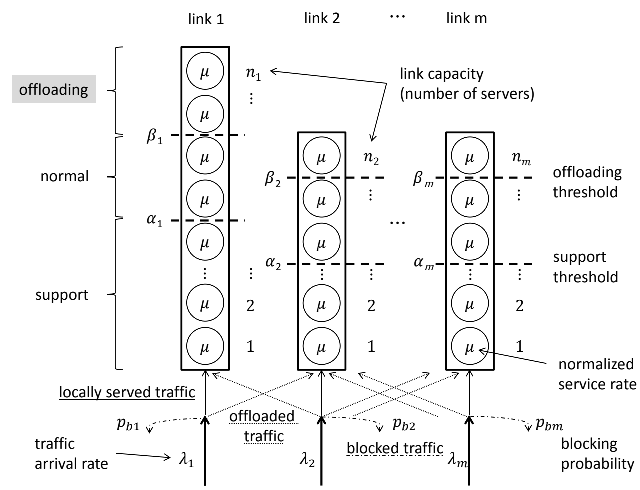


Figure 1: System model.

We consider the system in a short time frame, where the system load can be considered stationary. Each access link is modeled as a multi-server blocking system, in which each server represents an available bandwidth fraction of the link. Its utilization variations are modeled as a stationary process of singular and independent arrivals of traffic bursts, i.e., bandwidth fraction requests. Due to its convenient properties we assume Poisson arrivals of the traffic bursts. This allows modeling an access link as M/M/n loss system [29]. We define X as the random variable of the number of occupied bandwidth fractions on each backhaul link. It is modeled by a birth-death-process, in which bandwidth fractions are requested with Poisson arrivals at rate λ and occupied for an negative-exponentially distributed service time with globally normalized rate $\mu = 1$. Consequently, the load on each link is given by $\rho = \frac{\lambda}{n \cdot \mu} = \frac{\lambda}{n}$. The probability that k bandwidth fractions are occupied in the considered M/M/n queue is $x(k) = P(X = k)$.

In the BeWifi approach (cf. Section II), two thresholds are used, which define the bandwidth aggregation/offloading policy. The support threshold α indicates up to which percentage of utilization (i.e., number of own occupied bandwidth fractions) the system will offer bandwidth fractions to other systems. Furthermore, the offloading threshold β with $\alpha \leq \beta$ sets the percentage of utilization above which the system will try to use bandwidth of other systems. According to these thresholds, a system can be in one of the following three macro states:

1) *support* ($0 \leq X < \lfloor \alpha \cdot n \rfloor$):
   low utilization and offering bandwidth

2) *normal* ($\lfloor \alpha \cdot n \rfloor \leq X < \lfloor \beta \cdot n \rfloor$):
normal operation
3) *offloading* ($\lfloor \beta \cdot n \rfloor \leq X \leq n$):
high utilization and offloading to other systems

By applying the offloading policies, different Internet access links will collaborate and share traffic. More details on the investigated scenarios are presented in the following.

Two bandwidth aggregation systems, i.e., systems offloading between m access links, will be analyzed. First, we consider a bandwidth aggregation system with equal load on each access link. Moreover, a system in which one access link has a different load than the other $m-1$ links is modeled. As reference system we considered partitioned systems without offloading.

B. Reference System

We compare the bandwidth aggregation gain of multiple collaborating access links to a partitioned system without offloading. The received bandwidth of each access link $E[X_i]$ and the blocking probability p_{b_i} of each system i are evaluated. The blocking probability gives the probability that the link is fully utilized and a bandwidth request of an application cannot be entirely satisfied. In practice, if TCP is used on the access link, the Internet connections throttle themselves and share the link equally. Depending on the used application and its characteristics, the application performance can then suffer.

For completely partitioned systems, i.e., m different M/M/n_i loss systems with arrival rates $\lambda_i,\ i \in \{1, \ldots, m\}$, the received bandwidths $E_0[X_i]$ can be computed individually for each access link by Little's Theorem as

$$E_0[X_i] = \frac{\lambda_i}{\mu} \cdot (1 - p_{b_i}), \tag{1}$$

in which we use the rate of accepted arrivals $\lambda_i \cdot (1 - p_{b_i})$ and the globally normalized service rate $\mu = 1$.

The blocking probability of partitioned systems p_{b_i} follows from the Erlang-B formula [29]

$$p_{b_i} = \frac{\frac{(\frac{\lambda_i}{\mu})^{n_i}}{n_i!}}{\sum_{k=0}^{n_i} \frac{(\frac{\lambda_i}{\mu})^k}{k!}} \ . \tag{2}$$

C. Bandwidth Aggregation System with Equal Load

The case, in which m Internet access links offload traffic according to the policy defined via the support and offloading thresholds, is more interesting. In this section, we assume that all access links are equal ($n = n_i, \forall i \in \{1, \ldots, m\}$) and face equal loads ($\lambda = \lambda_i, \forall i \in \{1, \ldots, m\}$) and policies ($\alpha = \alpha_i, \beta = \beta_i, \forall i \in \{1, \ldots, m\}$). First, we distinguish one access link, and merge the remaining $m-1$ cooperating access links into a composite system. This reduces the problem of m systems to two systems. Still, the complexity of the composite system prohibits creating and analyzing the two-dimensional state transition diagram as it was done in [3]. Thus, we apply a fixed point approach to analyze this system.Therefore, we model an observed system, which will take into account offloading to and supporting the abstract composite system. For simplifying the notation, we define the macro state probabilities p_1 (support), p_2 (normal), and p_3 (offload):

$$\begin{aligned} p_1 &= \sum x(i), 0 \leq i < \lfloor \alpha \cdot n \rfloor \\ p_2 &= \sum x(i), \lfloor \alpha \cdot n \rfloor \leq i < \lfloor \beta \cdot n \rfloor \\ p_3 &= \sum x(i), \lfloor \beta \cdot n \rfloor \leq i \leq n \end{aligned} \tag{3}$$

In the support macro state, the arrival rate will be increased by λ_s, i.e., the arrivals that are offloaded by the composite system. λ_s can be computed as shown in Equation 4 from the multinomial probability that j of the $m-1$ links in the composite system are in offloading state, and k links in the composite system can support.

$$\lambda_s = \sum_{j=1}^{m-1} \sum_{k=0}^{m-1-j} \binom{m-1}{j} \binom{m-j-1}{k} p_3^j p_1^k p_2^{m-j-k-1} \frac{j\lambda}{k+1} \tag{4}$$

The arrival rate is decreased by λ_o in the offloading macro state when the composite system can support the observed system, i.e., at least one of the $m-1$ systems is in support macro state.

$$\lambda_o = (1 - (1 - p_1)^{m-1})\lambda \tag{5}$$

This gives new steady state equations for the observed system as described in Equation 6. As all access links have equal load, and thus, show a homogeneous behavior, not only the state probabilities of the observed system, but also of the $m-1$ systems in the composite system are influenced. Thus, the state probabilities of all m links can be obtained by computing the state probabilities of the observed system. Therefore, we initialize the observed system with equal state probabilities. Then, we iterate and normalize the state probabilities until a fixed point is reached.

$$\begin{aligned} x(i) &= \begin{cases} \frac{x(i-1)(\lambda+\lambda_s)}{i \cdot \mu}, & 0 \leq i < \lfloor \alpha \cdot n \rfloor \\ \frac{x(i-1)\lambda}{i \cdot \mu}, & \lfloor \alpha \cdot n \rfloor \leq i < \lfloor \beta \cdot n \rfloor \\ \frac{x(i-1)(\lambda-\lambda_o)}{i \cdot \mu}, & \lfloor \beta \cdot n \rfloor \leq i \leq n \end{cases} \\ \sum_{i=0}^{n} x(i) &= 1 \end{aligned} \tag{6}$$

For our modeled bandwidth aggregation system with m Internet access links, we consider the blocking probability $p_b = x(n) \cdot (1 - p_1)^{m-1}$ of a link, which is calculated by the probability that a request arrives when the link is fully loaded (i.e., in state n) and none of the $m-1$ other links can support.

Moreover, we take a look at the received bandwidth at each access link $E[X_{A_i}]$. Thereby, X_{A_i} is a random variable for the number of bandwidth fractions (in all systems), which are occupied by arrivals from system i. It is obvious that $E[X_{A_i}] = E_0[X_i]$ for the partitioned system. In case of offloading between m equal links, $E[X_{A_i}] = \frac{\lambda}{\mu} \cdot (1 - p_b)$ is equal for all links and can be calculated from the mean total number of occupied bandwidth fractions by taking into account the share of accepted requests. Finally, we quantify the percentage of bandwidth gain for each system as

$$\omega_i = \frac{E[X_{A_i}] - E_0[X_i]}{E_0[X_i]} \,. \tag{7}$$

D. Bandwidth Aggregation System with Imbalanced Load

Now, we consider the case of m systems, in which one link is different from the other $m-1$ links. Thus, we have the observed system with n_1 servers, arrival rate λ_1, and thresholds α_1, β_1, and a composite system of $m-1$ homogeneous links with $n' = n_i, \lambda' = \lambda_i, \alpha' = \alpha_i, \beta' = \beta_i, \forall i \in \{2, \dots, m\}$. This gives two different macro state probabilities p_1, p_2, p_3 for the observed system and p'_1, p'_2, p'_3 for the systems in the composite system, respectively, which can be computed analogously to Equation 3. The corresponding support rate λ_{1s} and offloading rate λ_{1o} of the observed system can then be computed as follows:

$$\lambda_{1_s} = \sum_{j=1}^{m-1} \sum_{k=0}^{m-1-j} \binom{m-1}{j} \binom{m-j-1}{k} p_3'^{j} p_1'^{k} p_2'^{m-j-k-1} \frac{j\lambda'}{k+1} \tag{8}$$

$$\lambda_{1_o} = (1 - (1 - p'_1)^{m-1}) \lambda_1 \tag{9}$$

These rates of supported and offloaded traffic cannot be easily integrated into the fixed point iteration of Equation 6 as they depend on the state probabilities $x'(i)$ of links in the composite system, which are in this case different from the state probabilities $x(i)$ of the observed system. To obtain the $x'(i)$ values, we introduce an inner model. This means, we again distinguish one of the $m-1$ links of the outer composite system, and merge the remaining $m-2$ links to an inner composite system. Although this inner model resembles the case described above in Section III-C, the equations for the inner observed system cannot be easily transferred, as the impact of the outer observed system cannot be neglected. Therefore, depending on the macro state of the outer observed system, the following support rate λ'_s and offloading rate λ'_o can be derived for the inner observed system:

$$\begin{aligned}
\lambda'_s = \\
& p_1 \sum_{j=0}^{m-2} \sum_{k=0}^{m-2-j} \binom{m-2}{j} \binom{m-2-j}{k} p_3'^{j} p_1'^{k} p_2'^{m-2-j-k} \frac{j\lambda'}{k+2} + \\
& p_2 \sum_{j=0}^{m-2} \sum_{k=0}^{m-2-j} \binom{m-2}{j} \binom{m-2-j}{k} p_3'^{j} p_1'^{k} p_2'^{m-2-j-k} \frac{j\lambda'}{k+1} + \\
& p_3 \sum_{j=0}^{m-2} \sum_{k=0}^{m-2-j} \binom{m-2}{j} \binom{m-2-j}{k} p_3'^{j} p_1'^{k} p_2'^{m-2-j-k} \frac{j\lambda' + \lambda_1}{k+1}
\end{aligned} \tag{10}$$

$$\lambda'_o = (1 - (1 - p_1)(1 - p'_1)^{m-2}) \lambda' \tag{11}$$

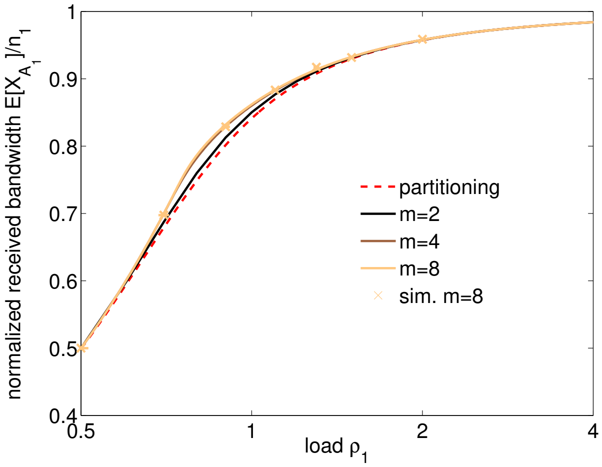
In Equation 10, the support rate λ'_s is computed for the case that the inner observed system can support. The summations consider the cases that j links want to offload and k links can support in the inner composite system. With probability p_1, the outer observed system is also in support macro state, thus, in total $k+2$ systems can support (including the k systems from the inner composite system and both the inner and outer observed systems) and share the offloaded traffic $j\lambda'$. With probability p_2, the outer observed system is in normal macro state and will not interact. It is in offloading macro state with probability p_3, which means that the offloaded traffic is increased to $j\lambda' + \lambda_1$ and shared by $k+1$ links. In contrast, the inner observed system can offload if the outer observed system is in support macro state, or at least one of the $m-2$ links of the inner composite model can help, which is reflected by Equation 11.

Solving this system by a joint fixed point iteration for the outer and the inner system, i.e., iterating and normalizing in turns over both systems according to Equation 6, will give the state probabilities $x(i)$ and $x'(i)$.

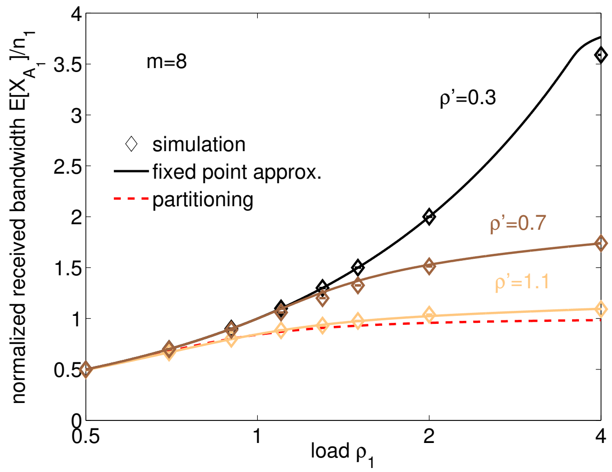
For the evaluation of this system, we will focus on the results for the outer observed link, i.e., the link that is not equal to the other $m-1$ links. For this link we will investigate the blocking probability $p_{b_1} = x(n) \cdot (1 - p'_1)^{m-1}$, the received bandwidth $E[X_{A_1}] = \frac{\lambda_1}{\mu} \cdot (1 - p_{b_1})$, and the bandwidth gain $\omega_1 = \frac{E[X_{A_1}] - E_0[X_1]}{E_0[X_1]}$.

E. Simulation Description

A discrete-event based simulation using arrival and departure events is implemented to validate the analytic model and to assess the system performance in more general cases. Each of the m systems has a Poisson arrival process with rate according to its load. The service time of bandwidth fractions is exponentially distributed with mean 1. Offloading decisions are made according to the the number of occupied bandwidth fractions in the systems with respect to the support and offloading threshold. Therefore, the simulation state holds the requests being processed and the number of occupied bandwidth fractions for each system.



(a) Equal load



(b) Imbalanced load

Figure 2: Normalized received bandwidth for (a) equal load with varying m and (b) imbalanced load.

IV. Numerical Examples

Using the model we aim to calculate numerical examples to evaluate the performance of the system in different scenarios. Therefore, the load on the observed system ρ_1 and the load on the composite system ρ' are used as parameters. We consider the normalized received bandwidth of the reference system $E[X_{A_1}]/n_1$ and the bandwidth gain ω_1.

To validate our model and to get a first assessment, we analyze the performance of systems with equal thresholds and compare the analytic results with the results obtained from simulation and those of a simple reference system. In this case the support and the offloading threshold are set to $\alpha = 0.7$ and $\beta = 0.8$ respectively. These threshold settings are used in the industry standard of BeWiFi [13], providing high offloading potential, while still preventing exploitation by free riders.

For a detailed evaluation of the impact of the threshold setting on the system performance for $m = 2$ cooperating systems, we refer to [3]. We then consider both cases to analyze the performance of systems with equal and imbalanced load. We conduct parameter studies to find system configurations where one of the systems can highly benefit from offloading, e.g., by being prioritized.

A. Equal Load

In this scenario, we assume that all access links are equal ($n = n_i, \forall i \in \{1, \ldots, m\}$), and face equal loads ($\lambda = \lambda_i, \forall i \in \{1, \ldots, m\}$) and policies ($\alpha = \alpha_i, \beta = \beta_i, \forall i \in \{1, \ldots, m\}$), according to Sec. III-C.

Figure 2a depicts the normalized received bandwidth $E[X_{A_1}]/n_1$ of the observed system depending on the load on each system for different numbers of cooperating systems m. The mean values with 95% confidence intervals of 8 simulation runs are plotted for $m = 8$ cooperating systems, as well as the received bandwidth in case of partitioning. The analytic results fit the simulation results showing the accuracy of the approximation. In any case the received bandwidth increases with the load on the systems. The systems benefits only slightly from a higher number of cooperating systems, if the load on the systems approaches 1. In this case bandwidth fractions can be offloaded to temporarily underutilized systems, which increases the received bandwidth.

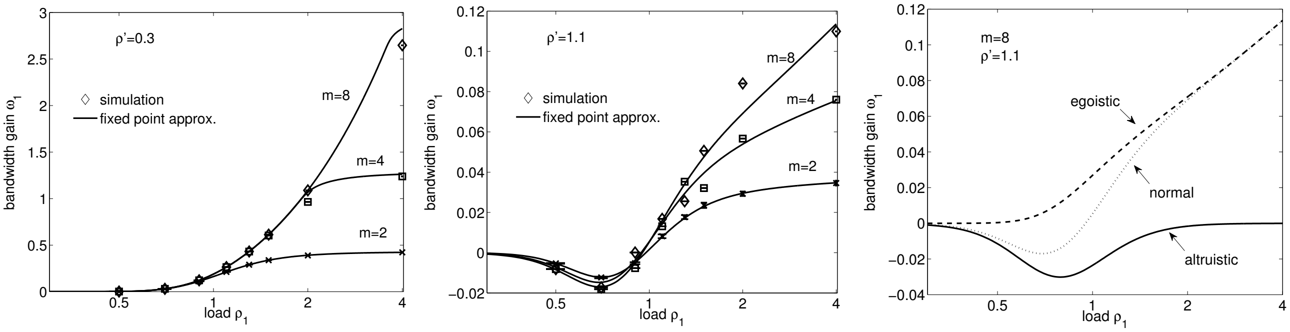
However, the received bandwidth is only marginally higher than in the partitioning case. This depends on the fact that the load is shifted back an forth among the cooperating systems. A higher number of cooperating systems will not increase the bandwidth gain, since there is already a saturation effect for up to $m = 8$ cooperating systems.

B. Imbalanced System Load

The cooperating system can benefit if the load is heterogeneously distributed among the systems, such that a system which is currently busy can offload to an idle system.

To assess the potential of bandwidth aggregation of m systems in heterogeneous load conditions, we study the load on the observed system ρ_1 and set the load on the other $m-1$ systems to the same value ρ', i.e., $\rho_i = \rho', \forall i \in \{2, \ldots, m\}$.

In the following we investigate how the load on the links in the composite system ρ' affects the throughput of the observed system for $m = 8$ cooperating systems. Figure 2b shows the normalized received bandwidth of the observed system dependent on the throughput of the links in the composite system ρ'. In case of $\rho' = 0.3$ a lot of spare bandwidth is available for offloading. If the observed system is overloaded it can use the spare bandwidth and receives almost 400% of its capacity if its load is 400%. If the load ρ' on the other links is higher, less bandwidth is available, which limits the received bandwidth. Still, the



(a) Off peak ($\rho' = 0.3$) (b) Overload ($\rho' = 1.1$) (c) Unfair: ($\alpha_1 \neq \alpha'$)

Figure 3: Bandwidth gain dependent on load of the observed system in off peak, overload and unfair operation.

received bandwidth is above partitioning, although the links in the composite systems are overloaded with $\rho' = 1.1$ if the observed system is even more overloaded.

Figure 3a shows the bandwidth gain of the observed system ω_1 dependent on the number of cooperating systems m for $\rho' = 0.3$. Hence, in this case there is a high potential to obtain spare bandwidth from the cooperating systems. Depending on the number of cooperating systems the bandwidth gain of the observed system is limited.

Figure 3b shows the bandwidth gain of the observed system ω_1 dependent on the number of cooperating systems m for $\rho' = 1.1$. In this case the links in the composite system are overloaded. This leads to a loss of up to 2% bandwidth, if the observed system is not overloaded itself. If the load on the observed system is high, but low enough that it supports other systems, a traffic burst is more likely to block the system, since the overall load is higher than in the partitioning case.

To conclude, if the load on the other systems is low, an overloaded system can highly profit from their spare bandwidth by gaining multiples of its own bandwidth. The maximum bandwidth gain is limited by the number of cooperating systems m. If the cooperating systems are overloaded, the received bandwidth might be up to 2% lower in some cases, but this is compensated with multiples of the base level bandwidth in high peak periods.

To prevent a system from being congested from an overloaded cooperating system, it can be prioritized. One possibility of prioritizing is to decrease the support threshold α, so that it still can offload to other systems, but shares less bandwidth fractions to support. Figure 3c shows the bandwidth gain of the observed system for three cases. The dotted line shows the blocking probability if observed and other systems have equal support threshold $\alpha_1 = \alpha' = 70\%$. The solid line shows the case where the observed system is altruistic and keeps its threshold at $\alpha_1 = 70\%$, but interacts with egoistic cooperating systems with support threshold $\alpha' = 0\%$. The dashed line shows the egoistic case where the observed system limits its support threshold to $\alpha_1 = 0\%$, while the cooperating systems support up to $\alpha' = 70\%$. The altruistic system suffers from egoistic cooperating systems by losing up to about 3% bandwidth while not being able to gain bandwidth in high loads. Compared to that, the bandwidth gain in the egoistic case is never negative. Hence, if a system is egoistic it always gains more bandwidth. However, the gain compared to normal operation is not high, and if each system would be egoistic no bandwidth can be shared. This would mean completely partitioned systems which would not change the current situation without bandwidth sharing. On the other hand, if a system is the only one sharing among only free riders, which corresponds to the altruistic case, the situation is not worse, since only about 3% of the bandwidth are lost. Thus it is a win-win situation if everybody contributes to the system and shares spare bandwidth. This provides incentives for systems to contribute.

V. Conclusion

To reduce the load on cellular networks and to cope with the increasing demand of traffic carried by mobile networks, traffic is offloaded to WiFi networks. To even increase the available bandwidth, recent concepts consider aggregating backhaul access link capacities. In this work an approximation of a partial sharing scheme is presented, which is used to analyze the performance of a system with multiple access links that share their bandwidth. A joint fixed point iteration of an outer and an inner composite system is used to derive the state probabilities in heterogeneous load conditions. In parameter studies we investigate the potential of the mechanism depending on the number of cooperating systems. Our results show that the bandwidth of an overloaded system can exceed its capacity multiple times if the cooperating systems are underutilized, especially if the number of cooperating systems is high. By prioritizing systems, we can show that the mechanism is robust against free riders and thus provides incentives to contribute to increase the overall system capacity. This is a very promising result for bandwidth sharing systems, since the offloading policy results in a win-win situation if everybody contributes by sharing spare bandwidth. This provides incentives for end users to participate and thus enables fast deployment of bandwidth sharing mechanisms.

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