Capacity and Interference Aware Ad Hoc Routing in Multi-Hop Networks

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***Abstract*: - This paper compares the influence of the routing metric on the network capacity of ad hoc networks extending hotspots in an urban environment. In recent years many research was invested in routing and mobility management of large ad hoc networks. However, this paper compares different routing strategies and presents a new routing metric that improves the achievable capacity for ad hoc networks extending an infrastructure considerably. We present an analysis on a high abstracted level, taking into account an urban environment and comparing our capacity and interference aware routing (CIAR) with two well known, state of the art routing strategies. The results show that in urban environments an intelligent routing protocol is able to enhance the network capacity significantly. The paper presents the improvement of the resource utilisation applying our capacity and interference aware routing, compared to the application of shortest path and largest bandwidth routing.**

***Keywords*: - Routing, Ad Hoc, Shortest Path, Largest Bandwidth, Interference aware, WLAN, Hotspot, Capacity, 5GHz, IEEE 802.11**

1. Introduction

Today's WLAN provisioning is achieved by deploying WLAN Access Points (APs) wherever needed, creating so called hotspots. Such a placement strategy is only reasonable in areas where the expected customer density is high. Nevertheless only a small fraction of those hotspots are able to work profitably. The investment of setting up a hotspot consists of the AP device costs and additionally of the costs for a wired connection of the AP to the existing infrastructure. Hereof the device cost is the far lower investment; the major investment goes into the wired connection of the AP [7]. The costs due to cabled installation limit the return of investment and are the reason why operators hesitate to rollout a citywide WLAN network, except certain hotspots.

In the last few years the idea of ad hoc networks attracted more and more attention. An ad hoc network consists of many independent and private terminals, owned by the end users. Those terminals cooperate and establish a multi-hop ad hoc network. Each terminal is able to relay data for all terminals in its vicinity. But until today, no real service could be found on the market using ad hoc networking. Some drawbacks among others of existing ad hoc networks are the missing Quality of Service (QoS) bases on the current lack of a suitable MAC protocol. However one of the driving ideas from ad hoc networks, using multi-hop connections, survived and is still assumed to be beneficial to extend the coverage and the service range of an AP.

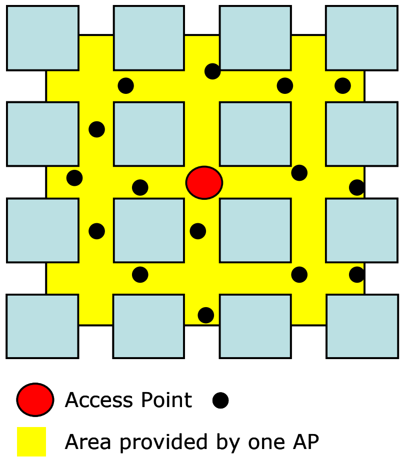

Fig. 1: City model [5]

With the help of multi-hop connections it is possible to shift the capacity provided at the close vicinity of the AP to the outer areas of a hotspot. One of the main tasks to realize this is the fast establishment of reliable and durable routes between AP and mobile terminal (MT). Most of the state-of-the-art routing protocols either base on the principle to establish short routes, i.e. the route using the minimum number of hops, or choose a route composed of links with the maximum bandwidth, in order to create a route providing a high data rate. But both principals neglect the overall impact on the network capacity. This paper presents a new routing metric using the interference of a link towards the AP as metric to find a new route that consumes less of the valuable network capacity at the AP.

This routing metric provides a higher network capacity utilisation. The benefit to use routes that minimize the interference to the AP will be shown within the paper. For it the overall network capacity is used to compare the new metric with the state-of-the-art routing metrics. The rest of the paper is structured as follows. The next section two presents the urban scenario which is used to compare the routing approaches. We give a detailed overview about the modelling of the physical resources and the network in section three. The performance evaluation and comparison, together with an in-depth description of the evaluated parameters is presented in section four. Afterwards we conclude our results and findings in section five.

2. Investigated Urban Scenario

Since WLAN coverage is only foreseen in areas where many people are present, such hotspots are usually in city centres. That means the routing protocols have to be able to handle the boundary conditions resulting from buildings, walls and other obstacles. But those obstacles affect the performance not only negative, in opposite an intelligent WLAN protocol, in conjunction with a resource optimized routing protocol, could benefit. By making usage of the compared to a line of sight scenario changed radio transmission conditions they are able to improve the network capacity. We focus our investigation on a simplified and standardized model, so called 'Manhattan Grid' of city centres, as it is proposed by the 3GPP group [1].

Frequency (f)	5.5 GHz
Background Noise (N_B)	-92 dB
Transmission Power (P_s)	200 mW
Wall Attenuation (θ)	11.8 dB
Attenuation factor γ	2

Table 1: Parameters of the Physical Channel Model

Fig. 1 shows this simplified model. The town is assumed to consist of homogeneous quadratic buildings and equal streets between the buildings. We assume that each building is 50x50 meters and the streets are of 20 meters width. A building consists of four walls. The power level of a radio signal traversing a wall is reduced by the wall attenuation θ, set to 11,8dB.

Data rate (Mbps)	Modulation	Coding rate (R)	Data Bits per Symbol
6	BPSK	1/2	24
9	BPSK	3/4	36
12	QPSK	1/2	48
18	QPSK	3/4	72
24	16-QAM	1/2	96
36	16-QAM	3/4	144
48	64-QAM	2/3	192
54	64-QAM	3/4	216

Table 2: PHYMode Dependent Parameters [2]

A signal crossing a building traverses two walls; hence the power level is reduced by 23.6 dB. The assumed wall attenuation can be understood as a lower limit. In most cases a building will reduce a traversing signal far more. An increasing number of terminals are uniformly distributed within the streets of Fig. 1. We assume that all traffic either comes from or goes to the AP. Each route contains 10% uplink and 90% downlink traffic, by this we model a typical web browsing traffic. During our investigations we either increase the traffic offered per route or the number of routes.

3. Evaluation Model

This work bases on a top-level analysis, modelling the resource consuming process which strongly depends on the routing principle. We distinguish models for the physical, link, medium access and network layer. The following subsections describe the layer models.

3.1. Physical Model

The physical layer model follows the IEEE 802.11a standard. The model bases on the distance between two terminals, the transmission power and the assumed background noise. We calculate the carrier to noise ratio for each communication pair. If we have J wireless terminals within a given surface, the position of each terminal $j \in [0 \dots J]$ is described by vector P_j.

$$P_j = (x_j, y_j)^T \tag{1.1}$$

The euclidian metric is used to calculate the distance between all terminals $i, j \in [0 \dots J], i \neq j$. Those distances are handled in matrix D.

$$D = \begin{pmatrix} d_{1,1} & \cdots & d_{1,J} \\ \vdots & d_{i,j} & \vdots \\ d_{J,1} & \cdots & d_{J,J} \end{pmatrix} \tag{1.2}$$

where

$$d_{i,j} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \tag{1.3}$$

Based on the distance between all terminals we calculate the carrier-to-noise ratio C/N (1.4).

$$C/N = \frac{\frac{P_s}{d^\gamma} \bullet \left(\frac{c_0}{4\Pi f} \right)^2}{N_b} \tag{1.4}$$

Table 1 presents the applied transmission parameters. Equation (1.5) calculates the carrier-to-noise ($cn_{i,j}$) ratio for all pairs of nodes, considering the wall attenuation θ of all intersected walls n. The results are entered into matrix CN (1.6).

$$cn_{i,j} = 10 \cdot \log_{10}\left(\frac{P_S}{d^{\gamma}_{i,j}} \cdot \left(\frac{c_0}{4\Pi f} \right)^2 \right) - \sum_{n=1}^{N} \theta_n(dB) - N_B(dB)$$

(1.5)

$$CN = \begin{pmatrix} cn_{1,1} & \cdots & cn_{1,J} \\ \vdots & cn_{i,j} & \vdots \\ cn_{J,1} & \cdots & cn_{J,J} \end{pmatrix} dB \qquad (1.6)$$

3.2. Link Layer

The physical layer of IEEE 802.11a offers 8 different PHYModes [2] presented in Table 2. In this context the term PHYMode stands for the used combination of modulation and coding rate. The first four bits within a packet preamble refer to the PHYMode used for coding the data payload [2]. The PHYMode is chosen depending on the quality of the link. Among other standards IEEE 802.11g utilizes the same PHYModes, therefore our results hold true for 802.11g as well. Fig. 2 shows the relation between C/N, and the packet error rate for the different PHYModes.

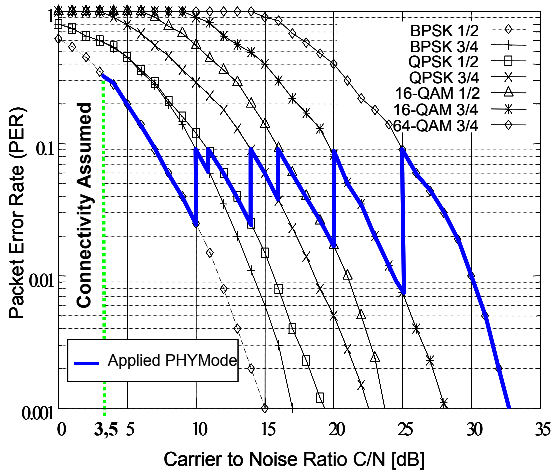

Fig. 2: Dependent Relationship between PHYMode and signal quality

Higher PHYModes are capable to deliver higher data rates, but need a considerably higher carrier-to-noise ratio to guarantee the same PER. In Table 2 all available modes are listed together with their maximum data rate, applied code rate and bits per OFDM symbol [2]. The maximum achievable data rate for each allowed PHYMode is combined in matrix M.

$$M = \{6, 9, 12, 18, 24, 36, 48, 54\}\, Mbps \qquad (1.7)$$

The IEEE 802.11a protocol allows choosing an individual PHYMode for each connection and each packet. Thus every terminal attempts to choose the PHYMode providing the best balance between throughput and packet error rate.

$$A = \begin{pmatrix} a_{1,1} & \cdots & a_{1,J} \\ \vdots & a_{i,j} & \vdots \\ a_{J,1} & \cdots & a_{J,J} \end{pmatrix} \qquad (1.8)$$

$$with \quad a_{i,j} = \begin{cases} 1 & if\ cn_{i,j} \geq 3.5dB \\ 0 & otherwise \end{cases}$$

For our evaluation we define two thresholds. A connection between two terminals i and j exists if the corresponding $cn_{i,j}$ is above 3.5dB (cf. Fig. 2). Under such conditions the most stable transmission modes (BPSK½) provides a PER of 35%. Taking into account that the packets are repeated up to five times ($(0.35)^5 = 0.0052$, resulting in a probability to loose a packet of 0.5%), we assume that a basic connection can be established. Matrix A is composed of all terminal pairs that fulfil the first condition (see equation 1.8). The second boundary condition is the packet error probability up to that a certain PHYMode is usable. For it we assume that the PHYMode has to be changed in case the according PER exceeds 10%. Both boundary conditions are applied to matrix CN. A PHYMode is used for a PER range larger 10% till the PER for the next higher transmission mode is less than 10%. The used link rate is the maximum rate of the set M that causes less than 10% packet errors under the given C/N ratio (see Fig. 2). The lowest PHYMode (BPSK½) is the only exception, in order to allow a basic connectivity.

$$LR = \begin{pmatrix} lr_{1,1} & \cdots & lr_{1,J} \\ \vdots & lr_{i,j} & \vdots \\ lr_{J,1} & \cdots & lr_{J,J} \end{pmatrix} \qquad (1.9)$$

$$lr_{i,j} = \max\{M(PER(cn_{i,j}) > 0.1)\}$$

Matrix A is transformed using matrix M and CN. The resulting link rates for each possible pair of terminals are stored in the link rate matrix LR (1.9).

3.3. Medium Access Layer

The main characteristic of a wireless network is the shared medium. Therefore the problem of channel allocation arises. Our evaluation handles interference of terminals by a time slot model which means when one terminal is transmitting all other terminals within its interference range have to back off. To implement he model we determine the interference range for every terminal taking the attenuation of buildings and walls into account. Terminals sense the channel and can only access the channel if concurrently transmitted signals are below the Carrier-Clear-Access (CCA) threshold of -82dBm [2]. Nevertheless, the access point can serve many terminals sequently by assigning time slots to all participating nodes. However, the more terminals are active the less transmission time is

available for each terminal. Our evaluation does not consider a specific link layer protocol with specific time slots, fixed frame sizes, contention problems etc. but models a ideal time division multiplexing access (TDMA): Each node in the network has limited transmission capacity (transmission time). The resource 'time' is consumed depending on the quality of its associated links. We determine the capacity for every node. When data is transmitted along a certain route, the transmission consumes the capacity depending on the amount of data, the number of hops and the applied PHYMode. One active terminal sending data along such a multi-hop path does not only consume the bandwidth of the direct involved hops (sender, intermediate nodes, and receiver) but also of all other terminals within the respective detection ranges. The proportion of consumed transmission capacity is the inverse data rate of the used PHYMode multiplied by the transmitted data rate. For example a MT sending 120 kbps data over a 12Mbps link, using QPSK½, consumes 1% of its capacity. Are other nearby nodes influenced, is their local resource reduced by 1 %, too. In this example, assuming that all used links share the same resource and operating at 12 Mbps, a maximum of 100 terminals can be served with a data rate of 120 kbps, before exhausting the capacity.
The number of served terminals is largely reduced when considering that multi-hop route are needed e.g. if the average number of needed hops is four, then the number of supported terminals is reduced by a factor of four, assuming that all share the same resource. In an urban environment buildings or obstacles decouple transmissions, and as such also decouple the sharing of the same resource. Thus the network profits from spatial reuse of the capacity. Our ideal model assumes a MAC Layer which assigns each transmitting terminal exactly the time slot length it needs. The slots vary in size and add up to represent the load of a node. When the available resource 'time' is consumed, the network/terminal becomes congested. We increase the data rate per user or the number of users, until the network congests and compare the resource utilisation for the different routing principals.

3.4. Network Layer

This section describes the implemented routing algorithms. These operate on the links provided by the link layer. A routing algorithm is necessary since terminals farther away need multi-hop routes to reach the AP.
We implemented three routing schemes, namely Shortest Path (SP), Largest Bandwidth per Connection (LBW) and Capacity and Interference Aware Routing (CIAR) and evaluated these in terms of imposed traffic load. An example scenario and the resulting routes for the different routing algorithms is given in Fig. 3. To calculate the best paths between all possible pairs of terminals for the three different metrics we use the Floyd-Warshall-Algorithm [3][4]. The calculation bases on the respective cost matrix, different for each routing principal. The cost matrix assigns a certain weight for each link between two terminals.

3.4.1. Shortest Path (SP)Metric

This approach selects the shortest path in terms of the minimum number of hops, ignoring the bandwidth of the selected links. For SP routing the cost matrix for the Floyed-Warshall-Algorithm is the single-hop matrix A. The algorithm's results are the distance between all pairs of terminals measured in number of hops stored in the multi-hop connectivity matrix *C* and the '*next hops*' stored in the matrix *NH* addressing the next hop for a given destination under the applied cost metric, details could be found in [3][4].

3.4.2. Largest Bandwidth per Connection (LBW)

LBW chooses the path between two nodes with the highest end-to-end bandwidth. The bandwidth is limited by the weakest link in the chain. LBW routes can be determined based on the link rate matrix *LR*.

3.4.3. Capacity and Interference Aware Routing

This routing scheme tries to minimize the traffic at the access point where it is typically concentrated. For each possible connection of two nodes we determine the cost in terms of load caused at the access point. The Floyd-Warshall-Algorithm is used to find the cheapest routes between any two nodes under this cost constraint. The cost weight for each link is determined by:

$$w_{i,j} = \begin{cases} \frac{K}{p(i,j)} & if\ cn_{i,j} \geq 3.5\,dB\ and\ \Pr_{i,AP} \geq CCA \\ 1 & if\ cn_{i,j} \geq 3.5\,dB\ and\ \Pr_{i,AP} < CCA \\ \inf & if\ cn_{i,j} \leq 3.5\,dB \end{cases} \tag{1.10}$$

K is constant such that $K/_{p(i,j)} \gg 1$ is always true. This constraint ensures that routes within the access point's interference range ((1.10) first case) are less attractive than those out of range ((1.10) second case). Equation (1.10) expresses that a link within the interference range of the access point gets a cost assigned that is proportional to the inverse of the link rate i.e. a lower rated link gets a high cost assigned and a higher rated link a low cost. All links that do not interfere with the access point get an equal cost of 1 assigned. This is because a cost value larger zero is necessary to avoid loops when using the Floyd-Warshall Algorithm [3][4]. Fig. 3 shows an example situation with one sender trying to reach the access point and the routes according to Shortest Path routing, Largest Bandwidth routing and capacity and interference aware routing. The link rates of the connections within interference range of the access point are shown in Mbps.

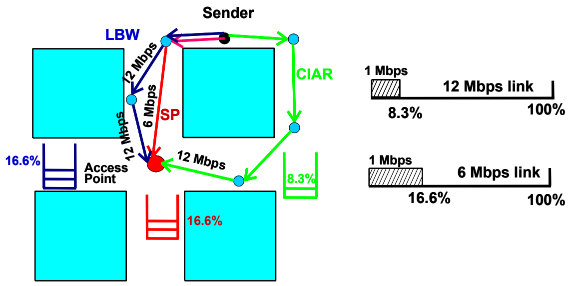

Fig. 3: Simulation with one sender trying to reach the access point and routes according to SP, LBW and CIAR.

This example assumes that the buildings shadow the signal completely and thus only line of sight transmission is possible. Therefore the load at the access point is only caused by transmitting terminals in line of sight. Furthermore, we assume that the requested data rate of the sender is 1 Mbps. The SP route has two hops, one interferes the AP using 6 Mbps transmission speed and consumes 1/6 ≈ 16.6 % of the access point's transmission capacity (see Fig. 3). The LBW route needs three hops, but two times 12 Mbps transmission rate and also consumes 1/12 + 1/12 = 1/6 ≈ 16.6 % of the access point's capacity. CIAR prefers a route with 4 hops and a rate of 12 Mbps, the capacity consumption is only 1/12 ≈ 8.3 % because only one terminal with a fast 12 Mbps link burdens the access point.

4. Performance Comparison

We choose the mean and maximum hop count and the mean and maximum capacity consumption for each routing principle as performance indicators. The focus of our work is the evaluation of an optimum routing principle in terms of resource usage. The maximum value of the local capacity consumption indicates where the capacity limit is reached first.

4.1. Evaluation criteria

Traditionally the efficiency of routing protocols is measured by looking at the hop count; we exploit the mean and the maximum hop count. The hop count is calculated based on multi-hop connectivity matrix C as a result of the Floyd-Warshall algorithm. Besides the hop count the most important is the (local) capacity consumption. Hotspot scenarios suffer from the bottleneck being of the AP.

$$\bar{h} = \frac{\sum_{i,j}^{J} c_{i,j}}{\sum_{c_{i,j}>0} 1} \qquad (1.11)$$

$$h_{\max} = \max\{c_{i,j}\} \qquad (1.12)$$

It is natural that all traffic has to go or to come from the AP. A routing metric decreasing the capacity usage of the AP would disburden the AP and improve the capacity of the network. Therefore we evaluate the maximum and mean load distribution.

We have a total of J terminals, K terminals are active resulting in K active routes and each route has a certain number of hops. We denote the n-th terminal of the k-th route by $R(k,nj)$ where $1 \leq n < J$ and $1 \leq k \leq K$. The number of hops of the k-th route is denoted by $N(k)$. The offered traffic r is equal for all terminals. The link rate matrix is denoted by LR. The matrix I contains the information if neighbour nodes share the same local resource, i.e. whether the detectable signal strength is above -82dBm. The local capacity usage $L(x)$ at each terminal x is calculated by:

$$L(x) = \sum_{k=1}^{K} \sum_{n=1}^{N(k)} \frac{r \bullet I(x, R(k,n))}{LR(R(k,n), R(k,n+1))} \qquad (1.13)$$

where:

$$I(i,n) = \begin{cases} 1 & \text{if } \Pr_{i,n} \geq CCA \\ 0 & \text{otherwise} \end{cases} \qquad (1.14)$$

Equation (1.13) expresses that the load at any terminal x is calculated by traversing all active routes in the scenario, and adding up the transmission time consumption of all nodes along these routes in case they are within the interference range of terminal x. The time consumption is equal to the used data rate divided by the link rate e.g. if the link is 24 Mbps and the used data rate is 6 Mbps then 6/24 = ¼ of one second is consumed by this link i.e. the load is 25%.

4.2. Performance Evaluation

Based on the evaluation criteria explained in the previous section. We investigated the scenario shown in Fig. 1. First we evaluated the different behaviors in terms of hop count. An increasing number of terminals are distributed within the streets of Fig. 1. We evaluate the mean and the maximum hop count. Each trial is repeated 100 times, in order to get the results independent from the terminal positions. Fig. 4 presents the mean and maximum hop counts, for an increasing number of terminals. The SP principle profits from introducing new terminals, since those might allow using a shorter path.

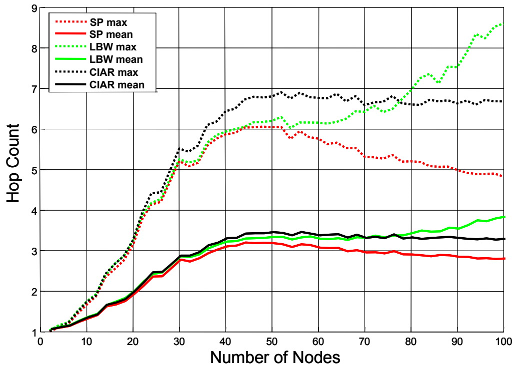

Fig. 4: Hop Count vs. Number of Nodes

The mean hop count for SP decreases slightly but the maximum route length rapidly decreases, with raising the connectivity. The LBW shows the opposite behaviour. LBW prefers short links with high data rate, therefore the hop count increases. The mean and the maximum hop count for CIAR converges at 3.2 in average, more terminals do provide more efficient routes, in term of optimized capacity usage. Fig. 5 presents mean and maximum local capacity utilisation. The investigated scenario consist of one AP in the city centre (cp. Fig. 1), 100 terminals, 50 terminals are active and request a duplex connection, each connection comprises 10 % uplink traffic an 90% downlink traffic (modelling a typical web browsing session). In case the offered traffic equals the existing capacity the local load at a terminal is 100%. Fig. 5 shows the local load averaged over each node and 100 trials.

	Traffic per route	Total Offered traffic	Changes cp. with SP [%]
SP	46kbps	2.3Mbps	-
LBW	42kbps	2.1Mbps	-8.69
CIAR	54kbps	2.7Mbps	17.4

Table 3: Results of the performance evaluation

The offered traffic per route for each connection is continuously increased. The maximum load is plotted as dotted line and the mean value as solid line. The network limit is reached when a terminal in the cell exceeds the existing capacity. Therefore we focus on the results of the maximum rather than on the mean. First the LBW principle exceeds the network capacity. LBW provides up to 50 connections each burdened with 42kbps. The SP approaches exceeds the local capacity at 46 kbps per route. The best performance can be observed by CIAR, providing 50 connections with 54 kbps. Table 3 concludes the results shown in Fig. 4,

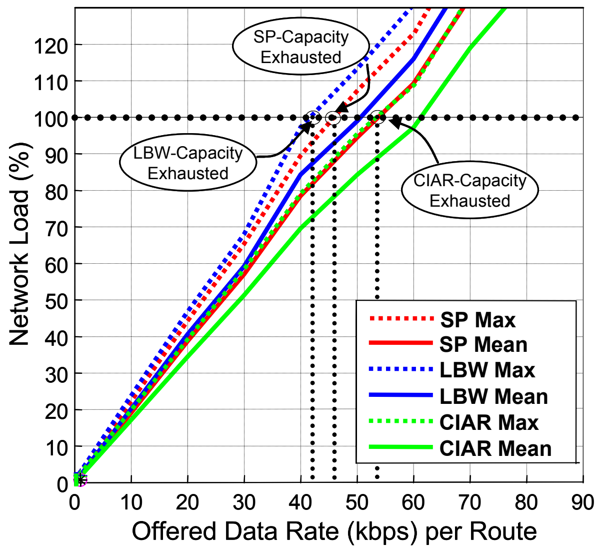

Fig. 5: Mean and Maximum Network Load

CIAR shows the most efficient resources utilisation. The SP principle is widely used in wireless multi-hop networks and can be understand as a quasi standard. The fourth column in Table 3 contains the changes on the resource usage compared to SP. LBW reduces the maximum network load, but might be usable in low loaded areas where high data rate routes are required. CIAR schedules the available resources very efficiently and allows increasing the transported traffic by 17%. Routing based on CIAR increases the efficiency of the capacity usage by the network.

5. Conclusion and Outlook

This paper presents a new routing metric optimized for wireless multi-hop networks extending the range of a hotspot by relaying the data transmission of an AP. Today most routing protocols, like Ad Hoc On Demand Destination Vector (AODV) routing, Dynamic Source Routing (DSR) or Destination-Sequenced Distance-Vector (DSDV) routing operate based on the shortest path principle. Today's WLAN protocols are capable to transmit using different PHYModes. We base our model on the IEEE 802.11a physical layer. However, the presented results are portable for other WLAN protocols facilitating different PHYModes.

IEEE 802.11a provides eight different PHYModes, these are used depending the link quality between sender and receiver. Besides the robustness, each PHYMode needs a different amount of resource to transmit the same amount of data. This paper presents a routing approach taking the resource consumption into account and choosing routes that disburdens the AP and thus, are able to increase the network capacity considerably. Today WLAN networks are not able to know how own transmissions influence other terminals, like the AP. But new designed WLAN protocols are able to provide that information [6]. Those new WLAN protocols in conjunction with advanced routing methods will improve the efficiency of multi-hop hotspot scenarios significantly.

REFERENCES

[1] B. Walke, “*Mobile Radio Networks*”. New York, USA: Wiley & Sons Ltd., 1. ed., 1999.

[2] IEEE, “*IEEE Wireless LAN Edition - A compilation based on IEEE Std. 802.11 1999(R2003) and its amendments*”, IEEE, New York, Standard IEEE 802.11, Nov. 2003.

[3] R.W. Floyed *Algorithm 97 shortest path. Communication of the ACM*, p.p. 345-346, 1962

[4] S. Warshall. *A theorem on boolean matrics*. Journal of the ACM, 22(9) :11-12, 1962

[5] ETSI Universal Mobile Telecommunication Systems UMTS. ”*Selection procedures for the choice of radio transmission technologies of the UMTS*”. ETSI UMTS 30.03 version 3.1.0, 1999

[6] G. Hiertz, Y. Zang, J. Habetha, H Sirin, ”*IEEE 802.15.3a Wireless Personal Area Networks - The MBOA Approach* ”. 11th European Wireless Confer--ence 2005, p.p. 204--210, Nicosia, Cyprus, 2005,

[7] R. Pabst, T. Irnich, B. Walke, ”*Weighted Spectral Efficiency for the Comparison of Candidate Future Radio Access Technologies*”. 11th Wireless World Research Forum, WWRF, Oslo, Norway, 2005