INTELLIGENT CACHING STRATEGY FOR MOBILE COMMUNICATION NETWORKS

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Abstract - Modern mobile radio communication will bring wireless broadband access to all users. However a full coverage even in urban areas is not accomplishable or reasonable. In fact there will be a high density of Hot Spot zones offering several 10 Mbit/s of bandwidth and zones of only limited access via cellular networks like GSM/GPRS or UMTS in between. The employment of intelligent caching strategies will increase the overall performance of such heterogeneous network structures and virtually extend broadband access towards a full coverage. Intelligent caching is based on the principle of buffering information in advance in periods of high transfer rates and consuming them during idle episodes between these zones. Therefore it is benefecial to optimise download rates in such specific areas. Customers will get the impression of a continuous wideband connection.

The paper will expose the performance gain due to caching strategies and how future WLAN networks have to be dimensioned for optimal usability. The new concept can overcome the problem of patchy coverage and provide a virtually continuous broadband Internet access.

Keywords - Intelligent caching, future mobile communication, network concepts, virtually always connected.

I. INTRODUCTION

The emerging of mobile communication has introduced new challenges to network and protocol designers. The preferences and requirements of wireless communication are significantly different from wired networks. Moreover new wireless communication standards have to be included into the common IP-structure of the Internet.

To deal with these new challenges a couple of protocols and techniques [1] [2] are currently invented and standardized. New caching strategies are a most promising approach for further support of mobile communication.

As wireless links are subject to link losses, high jitter in throughput or delay and frequent handovers, the network has to react much more on alterations in connection performance as used from cabled ones. The Internet as the common backbone for all future communication networks has currently no features to deal with such problems. The caching of data close to the wireless hop at the edge of the core network would partly overcome these. The communication between a data source and the consumer is separated by a caching entity so that the first segment is exclusively confined to wired networks and therefore it is manageable by legacy technology. All issues regarding the radio data transfer are then restricted to a very limited region and much easier to handle. This paper proposes the location of caching nodes strategically located in areas of massive wireless communication like densely populated urban areas or highly frequented motorways. By grouping access points (AP) and base stations to clusters a user moving in such an area would be continuously under the coverage of one caching entity. This implies that after switching over to another cell the same caching node can be employed and accessed.

In section II the motivation for new caching strategies is outlined. A description of suitable application areas follows in section III. Afterwards the system concept is introduced and explained in more detail. Moreover the improvements for the overall performance and the end user's convenience are given. A mathematical analysis for the proposed intelligent caching concept is given in section IV. Furthermore an estimation for the dimensioning of future mobile broadband networks is introduced. Section V provides an outlook for additional features which in the future could lead to further improvements of the overall system. Finally, in section VI the paper is summarized and concluded.

II. MOTIVATION

The Internet is currently undergoing its most significant changes in history. Just as the emerging of world wide connected computers has revolutionised consumer behaviour and communication in recent years the future will be lead by wireless technologies.

In a survey among 40 technology's "Masterminds" the question about the "most important technology for the coming decades" was answered with the simple statement "Wireless" [3]. People were made used to an unlimited information exchange around the world. Now they want to take these opportunities out of there homes and offices. Therefore the Internet has to get mobile.

Recently, of course, a lot of different mobile communication standards have emerged. The 802.11 technology is widely spread around the world and is continuously improving in bandwidth and mobility support. New cellular systems like UMTS are approaching and try to catch up the head start of WLANs regarding user acceptance and number of enabled devices.

But due to several reasons, like ubiquity, mobility, or bandwidth, no current system will be capable of supporting mobile communication as it is expected by customers and vendors.

New 4G standards have to provide mobility to users so that the performance differences between fixed and wireless systems almost disappear. Bandwidth and delays have to proceed into the same dimension to make discreapancies marginal.

III. Scenario Description

The main field of application for the proposed caching system are areas of frequent access to WLAN Hot Spots where no continuous coverage is achievable or financially reasonable.

These are urban areas in which outdoor WLAN access is provided by APs mounted on traffic lights and lamp posts or directly attached to exterior walls of buildings [4]. Another field will be motorways where the access points are attached to racks of traffic signs so that within certain intervals WiFi coverage is provided.

In both case the connection between terminal and AP is interrupted frequently. On motorways the distance between successive access nodes is too far to allow effective transfer rates permanently. In urban areas the density of WLAN cells is in fact much higher but due to shadowing the illumination of APs is very limited. Future mobile communication systems will work in higher frequency bands to support the desired data rates. But simultaneously fading effects are reduced and line of sight propagation between communication partners is necessary so that the smallest obstacle makes a data exchange impossible [5]. So in either scenario the WLAN sessions are interrupted frequently and need to be re-established very often. Each session recovery necessitates an end-to-end connection re-establishment which would be affected by backbone delays and link congestions.

IV. System Concept

The approach for enabling intelligent caching is based on the grouping of several access points towards a bigger cluster. All WLAN access points of one specific region, namely the downtown area of cities or a longer section of a motorway, are combined to one cluster and connected to a network node with caching functionality. There are no specific requirements made on these links and legacy network connections can be employed for it. The caching node itself is attached to the Internet so that the access to services and data is guaranteed.

If a user requests information from a server somewhere in the Internet the data is routed not directly to the actual destination node but to the associated caching node. And from there on the packets are forwarded to the terminal. Furthermore if the terminal leaves the WLAN cell the transfer of data is not interrupted like in today's networks but the caching node continues the download and buffers the received packets.

If the connection is re-established within the same WLAN cell a fast recovery of the data transfer is possible. Instead of waiting until a new request has traversed the backbone towards the server and the corresponding answer vice versa, the distance between the source of packets and the destination is rather short and the packet flow can start much faster. But the major advantage of the systems occurs if old and new access points differ. In the aforementioned scenarios it was stated that no regular inter-cell handover can be accomplished as the terminal never resides in two cells at the same point in time. So the session recovery would require negotiations and a re-transfer of packets through the whole core network. By forming clusters with a centralized caching node out of AP in closer proximity the probability of being in the same cluster is very high. Therefore the session does only need to be re-established between the terminal and the caching entity. All delays and limitations of the backbone network are avoided and the flow of data is optimized. The end-to-end connection between server and client is separated into two sections. Within the first segment the data transfer can proceed continuously as no interruption takes place. All incoming data packets are buffered and the final delivery via the wireless link is postponed until the terminal comes into coverage range of a WLAN AP.

This strategy implies two benefits for the overall system. Firstly, the traffic through the core network is smoothed as peaky data transfers are cut and a steady stream is established. The reduction of the data rate's variance would have a strong impact on the dimensioning of backbone links as the maximum capacity can get closer to the average transfer rates. Secondly, the utilization of the wireless link is optimised. Since the requested data packets are already available close to the access points the transfer can start almost immediately and longer end-to-end delays caused by the core network are avoided. Furthermore the transfer rate is only limited by the capacity of the wireless link and no longer affected by congestions and link overloads or failures within the backbone network.

V. Simulation Scenarios and Results

The performance of intelligent caching vitally depends on the chosen scenario and the preferences of WLAN networks. There are major differences between urban environments and rural areas, namely user's mobility, cell density, and propagation models. Therefore two different scenarios are studied in the following, an urban and a motorway setup. The inquired multimedia services are limited to asymmetric data transfers with high bandwidth requirements, like video streaming or FTP downloads. Other services can be covered by cellular systems like UMTS but especially applications with high data rates are restricted to WLAN systems. Video streaming through the Internet varies in throughput and respectively quality. New codecs are highly adaptive so that they can match almost every available throughput which is ruled by end-to-end network and last mile connection capacities. Therefore it is difficult to state a reasonable transfer rate for future video streaming. Based on current research data a rate of 700 kbit/s for high quality video streaming as an average transfer rate is assumable [6]. Furthermore the modelling of

WLAN capacities has to follow as well present or near future WiFi properties. The developed results are an estimation of available performance improvement on the basis of current radio, network, and streaming capabilities.

The scenario setup for urban areas consist out of a user with low mobility and a medium up to high density of WLAN access points. However due to propagation effects like shadowing and fading full coverage is not reachable. Hence with legacy technology and protocols video streaming would be interruptive and inconvenient. Although buffering is already employed in current streaming standards it is not capable of bridging longer idle gaps between different cells. Even a strong interworking between cellular systems and wireless LANs would stand for high quality during WiFi coverage and rudimental performance during the fallback solution. Only the caching of an adequate amount of data while connected via a high-speed link can overcome the problem. But this fails because of the limited backbone throughput. New WLAN technology offers data rates up to several 10 Mbit/s but the end-to-end throughput is usually still limited to less than 1 Mbit/s. Which implies that not the wireless link is the limiting factor in throughput.

Therefore it is assumed to have a smaller than 1 Mbit/s end-to-end link between the source and a caching entity close to the AP and an up to 6 Mbit/s connection between the cache and the mobile terminal (limited by the wireless link). Obviously, the latter rate is smaller than the maximum capacity of wireless LANs, but especially in dense populated areas there is a competition between different users and technologies. Hence interference can limit the overall performance and the capacity has to be shared with other customers, so that only a part of the maximum throughput is available for each user.

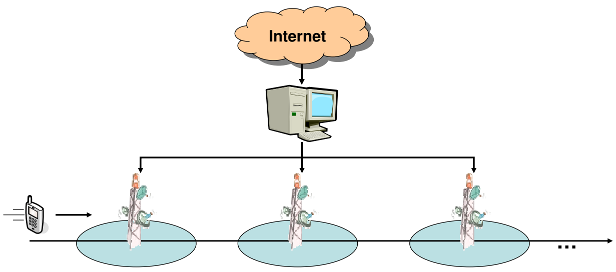

Fig. 1. Clustering of Non-overlapping WLAN Cells

The simulation model consists out of a number of subsequent WLAN APs which do not overlap but have idle gaps in between as depicted in Figure 1. A user is traversing the scenario from one cell to another while the terminal is buffering multimedia during WLAN coverage to bridge the idle periods. It can be assumed that by employing intelligent caching requested data is already available at a caching node close by (represented by the PC on top of Figure 1) and therefore the download rate (r_d) is no longer limited by the backbone delays and traffic but only by the capability of the radio link. Therefore rates between 2 and 6 Mbit/s can be expected and on that account are used for the evaluation.

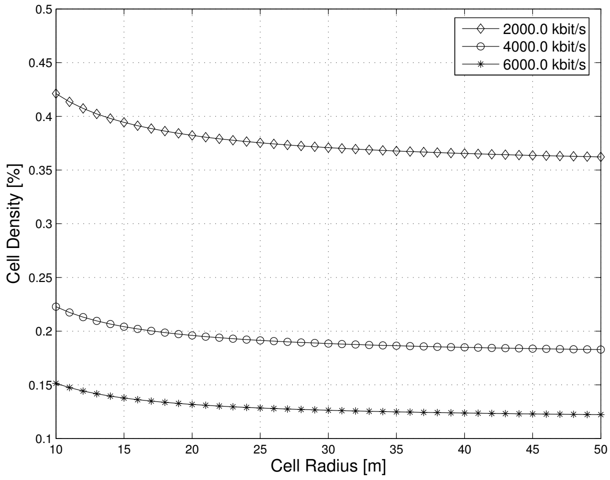

Fig. 2. Cell Density depending on Cell Radius in Urban Areas

In Figure 2 the dependency between the cell radius (R) and the relative cell density is given. The more a terminal can buffer while inside a WLAN cell the further the displaying of a video can continue before the data is exhausted. This means that the user can bridge a longer distance between adjacent cells. For the evaluation a constant velocity (v) of 2 m/s was assumed. As soon as the terminal enters the coverage area on an access point it starts to associate to the network and which contains that among other things protocols like DHCP has to be accomplished. During this registration period no user data can be transported. So not the whole sojourn time (d_s) can be used for buffering but an association time has to be subtracted. Experiments with a demonstrator [7] have shown that a reasonable duration for the association period (t_{assoc}) amounts to 2.6 seconds with today's protocols.

$$d_{net} = \frac{2 * R}{v} - t_{assoc} \tag{1}$$

$$X_{buf} = d_{net}(r_d - r_s) \tag{2}$$

$$D_{cell}(R) = \frac{2 * R}{\frac{X_{buf}}{r_s} v + 2 * R} \tag{3}$$

The within the net download time (d_{net}) buffered data (X_{buf}) (compare Equation 1 and 2) is consumed right after leaving the coverage. The bridging time and distance therefore vitally depends on the download rate of the wireless link. In Figure 2 the relation between idle and busy periods of WLAN access are depicted as a function of the cell radius. As a parameter the available download rate was chosen. It can be seen that the higher the throughput within a cell is the smaller the required density of access points needs to be. For a rate of 6 Mbit/s the cell density (D_{cell}), developed in Equation 3, can be less than 15%. This implies that future deployment scenarios for urban areas do not need to necessarily provide a full

WiFi coverage. An interworking with cellular systems could overcome the problem of continuous access to the Internet, while bigger data transfers are postponed till higher transfer rates are available. In Figure 2 it is also shown that the required density decrease with raising cell radius. The bigger cells are the smaller is the impact of the association time. So if the terminal has finished the association procedure shortly before leaving the cell almost no user data can be transferred and buffered. Whereas a long sojourn time makes the effect of t_{assoc} marginal. This makes it reasonable to mount access points at highly frequented areas with free vision in all directions in downtown areas like crossings so that the sojourn time is as big as possible. Then an average download rate of 700 kbit/s (r_s), as in the above example, can be reached with WLAN coverage between 20 and 30% of the whole area.

The requirements for a broadband communication system heavily depend on the scenario and the environmental settings. As the density of customers in rural territories is much smaller than in urban areas a comparable provision of broadband access will never be reasonable. Nevertheless it would make sense to provide a better service at highly attended places like motorways and freeways. The user density is comparable to downtown areas. Passengers, with no particular function, have enough spare time to watch videos and surf the Internet. Up to now broadband access failed due to the high velocity of the terminals. In the future new PHY modes will make it possible to offer much higher bandwidth even for fast moving users. However a full coverage of every freeway track section would imply major deployment costs. Contrary to that an illumination in non-overlapping sections with idle gaps in between would be much cheaper and easier to accomplish. Access points could be mounted on traffic signs and connected to the Internet via cabled connections or beamed radio comparable to current solutions for the link-up of base stations of cellular systems.

As already mentioned before services with minor capacity requirements could be provided by ubiquitous GSM-like networks while the transfer or bigger amounts of data would only takes place in successive HotSpot areas. The major issue for such a scenario is the interval size between APs for a sufficient service provisioning. As an exemplary service video streaming with the aforementioned average transfer rate of 700 kbit/s is chosen. Although no WLAN technology exists for the communication to high velocity units there are predictions for 4G techniques available yet. For example the new IEEE 802.20 standard, Mobile Broadband Wireless Access (MBWA), tries to develop radio communication for velocities of up to 250 km/h with a cell capacity in the order of magnitude of several Mbit/s [8]. This can be used as an indication for the layout of motorway broadband communication systems. The cell size should be limited to connections with the highest performance. Otherwise more distant terminals with less capable connections would consum a disproportionate partion of the overall bandwidth. Inherently this maximizes the performance of the whole cell. Therefore the cell size is limited to a radius of 200 m [9].

The sojourn time of vehicles in a cell depends on the velocity. The faster a car moves the smaller will be the buffered amount of data. In Figure 3 it is shown the maximum distance between adjacent access points (D_{int}) depending on the user's velocity which is varied between 70 and 180 km/h.

$$D_{int}(v) = \frac{X_{buf}}{r_s} v + 2 * R \quad (4)$$

The depicted curves correspond to download rates between 2 and 8 Mbit/s. It can be seen that for the highest transfer rate the interval between the APs is up to 4 kilometres. For a cell diameter of 400 meter this corresponds to a cell density of 10% which implies that deployment cost would be dramatically reduced. But even with a download rate of 2 Mbit/s less than 50% coverage is required to bridge idle gaps.

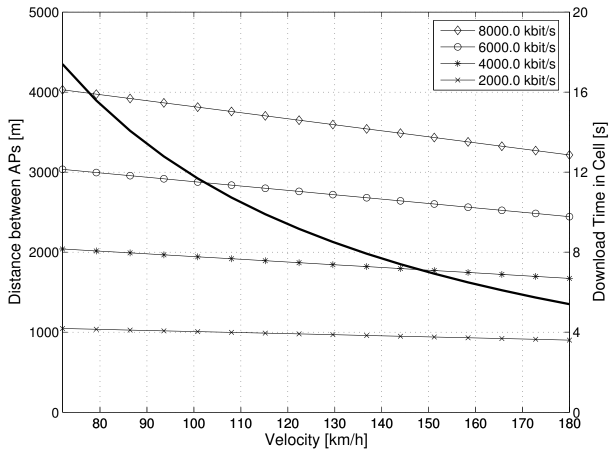

Fig. 3. Distance between Successive APs and Download Time depending on User Velocity [Single User]

Moreover it is noticeable that all curves decrease with raising velocity and that this effect is amplified with a higher download rate. This is related to the impact of the association time on the overall performance. As it is a fixed duration the net download time is decreased by a fixed value independent of the velocity. So the faster a vehicle is traversing a cell the bigger the effect of the association procedure gets and the same is valid for higher download rates as the amount of buffered data is caused by the net download time and not the sojourn time. However, the time d_{net} also decrease with raising velocity as depicted in Figure 3 (curve corresponds to the y-axis on the left hand side).

The previous investigations about a freeway scenario were limited to one user per cell. In a realistic environment more than one vehicle is using the freeway and if the distance between two successive cars is small enough the bandwidth of an access points is used by more than one party; presumed that each user has an ongoing Internet, respectively video streaming session. To estimate the number of simultaneous users per cell two factors have to be regarded. Firstly, the average distance $(d(v))$ between vehicles is significantly depending on the travelling velocity and, secondly, on the portion of users which simultaneously require broadband wireless Internet access $(ratio)$. For the first factor a lot of investigations were carry out, especially for traffic management and simulation reasons, while the second one is hard to evaluate. It is related to the ratio of vehicles with more than one passenger, as the driver cannot be considered as a network consumer for video streaming or bigger file transfers. On the other side the Internet access for fellow passengers could significantly change the customer behaviour in such scenarios as the services like video streaming in vehicular environment would be completely new. For the later evaluations a portion of 20% is assumed which can be seen as an upper limit for realistic scenarios.

The evaluation of the distance between successive cars is taken from enquiries about the impact of cruise control, a standard feature for next generation cars, on future traffic behaviour [10] and an analysis of British motorway driver behaviour [11]. An approximation of both results leads to the following linear dependency between distance of successive cars (d) and travelling velocity:

$$d(v) = m * v + b = \frac{1}{3}v[m/s] + 5m \tag{5}$$

If several users within one WLAN cell want to receive data simultaneously they have to share the overall capacity which leads to a reduced effective download rate and therefore to a smaller amount of buffered data. The average number of active users (n) within a cell for the proposed freeway scenario is

$$n = \frac{2 * R}{d(v)} * \frac{1}{ratio} \tag{6}$$

which yields a size of buffered data of

$$X'_{buf} = \frac{d_{net}}{n}(r_d - r_s) \tag{7}$$

and consequently an interval size of

$$D'_{int}(v) = \frac{1}{ratio}(d(v) - \frac{t_{assoc}d(v) * v}{2 * R})(\frac{r_d}{r_s} - 1) \tag{8}$$

which is depicted in Figure 4.

To assess the suitability for future deployment concepts it is important to estimate the required interval size between WLAN access points. In the previous evaluation gaps of 4000 m could be bridged. Certainly this was a best case estimation as only one user was considered. For the more sophisticated model the results are shown in Figure 4.

For reasonable average travelling velocities between 120 and 140 km/h intervals of up to 2400 m are reached. That corresponds to a coverage density of 17%. Less than one fifth of a freeway has to be provided with broadband wireless access to substantially increase average download and streaming rates.

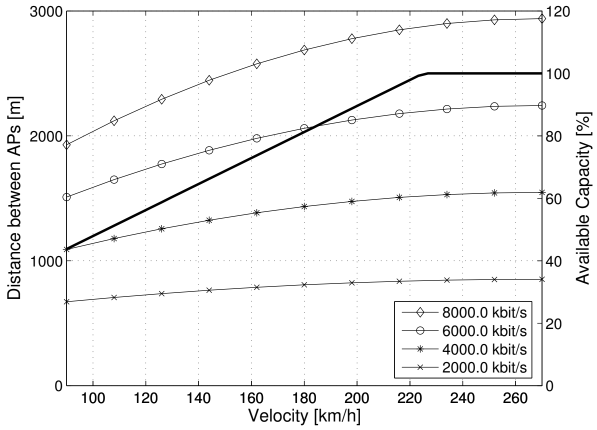

Fig. 4. Distance between Successive APs and Download Time depending on User Velocity [Multiple User]

But even for a medium download rate of 4 Mbit/s the distance between access points accounts for values of 1100 m up to 1500 m which matches a density of about 30%.

Much more noticeable is the reverse gradient of the curves compared to the previous example. Although a higher velocity reduces the sojourn and therefore the download period more data is buffered. This effect is caused by the raise of safety distance between cars. Due to these bigger intervals the density of users which are simultaneously within one cell is reduced and the shared capacity per user is increased at the same time. Both implications partly compensate each other but for the chosen velocity area the impact of the raising safety distance prevails. To get an impression of this effect in the same graph also the available capacity per user depending on the velocity is depicted (graph belongs to the y-axis on the right hand side). Starting form a portion of less than 50% for a velocity of 100 km/h it linear increase towards 100%. Nevertheless the latter value corresponds to a travelling velocity of more than 220 km/h which is not reasonable for near future traffic scenarios. Also an available capacity of more than 100% is not rational but it only expresses the fact that during certain periods no active user at all is within the cell. Therefore the curve is cut from this point and limited to the maximum share of capacity.

It can be concluded that for the given utilization ratio of 20%, the cell size, and the assumed distance model the capacity share (C) per user lays between 45 and 70%. So it can be expected that each user posses about half of the cell capacity while being within the coverage range of the access point.

$$C = \frac{d(v)}{2 * R * ratio} \tag{9}$$

In Figure 4 it could be seen that the graphs raise with increasing velocity although the effect of the diminishing download time would imply a different behaviour. Nevertheless they seem to reach a maximum at the end of the curves which would mean that the antagonistic effects are compensating each other or even more that starting from a certain velocity the other one dominates.

The interval between APs for higher velocities is depicted in Figure 5. It can be seen that after reaching a maximum the curves start to decrease again. However for the chosen parameters this effect takes place only for a velocity of more than 250 km/h and hence it is irrelevant for the proposed scenario. This concludes that within reasonable limits the capacity always increase with raising velocity. Moreover the maximum seems to be independent of the available overall capacity of the WLAN cell. For the right hand side y-axis the gradient of the 8 Mbit/s graph is given. The curve has its zero-crossing obviously at the maxima of the other graphs and proceeds to negative values afterwards.

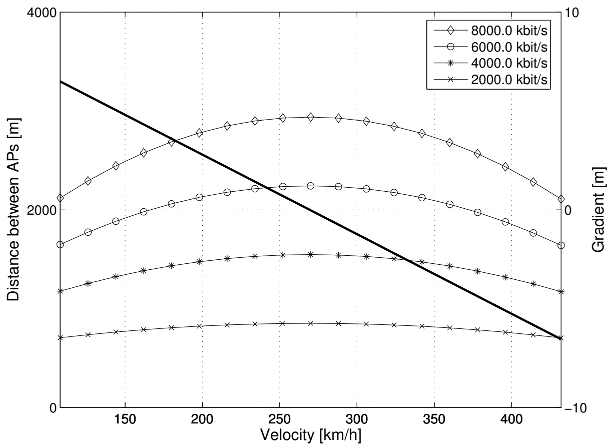

Fig. 5. Gradient of Motorway Scenario Analysis

The gradient (M), shown in Equation 10, as the differentiation of D_{int} depends on several parameters. Nevertheless the maxima seem to remain constant. Therefore in the following the major influencing variables are identified.

$$M = \frac{d}{dv} D'_{int} = \qquad (10)$$

$$\frac{1}{ratio}(\frac{r_d}{r_s} - 1)(\frac{d}{dv}d(v) - \frac{t_{assoc}}{2 * R}(\frac{d}{dv}d(v) * v + d(v)))$$

To locate the maximum of the prior curves the gradient is set to 0 which leads to condition

$$v = \frac{R}{t_{assoc}} - \frac{b}{2m} \approx \frac{R}{t_{assoc}}, \qquad (11)$$

where m and b are the slope and respectively the axis intercept of $d(v)$. For the given parameter set the first fraction significantly dominates the term. Therefore the point where both effects compensate each other only depends on the cell size and the necessary association time. Hence even for varying portions of active users or changing streaming and download rates the interval between successive APs will increase with raising velocity. Also the traffic model for the safety distance has only a minor impact on it so that necessary approximations can be neglected for the aforementioned evaluations and considerations.

VI. Further improvements

In the previous concepts and analyses intelligent caching was introduced as a key functionality for new mobile broadband communication networks. However a further improvement can be reached by employing stronger interworking mechanisms between WLAN and cellular systems like UMTS. While the latter technology is used to provide a ubiquitous access for each user WiFi will allow higher bandwidth at reasonable places. By requesting information via cellular systems if no WiFi is available the data could be already cached at a close-by node even before a WLAN cell is entered. Nevertheless future handheld devices or laptops will have the possibility to determine their own position, either actively by e.g. GPS-positioning or passively by localisation carried out by the base stations. These methods, mainly invented for location based services, could be used to estimate which WLAN cell is entered in the near future. This information can be used to provide buffered data exactly at the closest caching node even before the terminal comes into range of the WiFi access point.

By composing user profiles of frequently accessed information and the gathering of personalized data like mails a packet of relevant data can be hold out at such a caching network node, so that the data is cached even without an explicit request by the user. After the first broadband access the data is transferred to the end device. If the user then demands such kind of data an up-to-date image is already on its device and can be used immediately even without any connection to the Internet at all. Although this transfer can be executed as well in cellular systems due do cost constraints and available download capacity wireless LANs are much more suitable for such purposes.

VII. Summary and Conclusions

Within this paper a new concept based on intelligent caching was introduced. By clustering WLAN access points and potentially base stations of cellular systems within closer vicinity together with one caching node at the edge of the core network the end-to-end data flow can be optimized. Moreover a ubiquitous virtual broadband connectivity for non interactive services can be established.

The paper has shown that in urban areas a reasonable WLAN provisioning can be reached by an effective coverage of less than 20%. These results may have a significant impact on the dimensioning and deployment of next generation WiFi networks. Moreover the evaluated motorway scenario could broaden the horizon of multimedia services. By using the uniformity of motion and placing WLAN APs in certain intervals an overall throughput can reached sufficient for high quality video streaming or high speed data transfer. The problem of a ubiquitous broadband coverage in rural areas can be overcome at certain locations simply by maximising the system performance in specific areas. Compared to other approaches the deployment cost could be lowered dramatically by small changes in protocols and backbone devices.

Intelligent caching is a most promising approach for next generation communication systems and will allow completely new concepts in network design and service provisioning.

VIII. Acknowledgments

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