Fixed and Planned Relay Based Radio Network Deployment Concepts

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***Abstract*— It is widely accepted that multi-hop communication will become an integral element in *beyond 3G (B3G)* broadband networks, because the area that can usually be covered by a single *Access Point (AP)* is inherently small. This paper elaborates on the potential of a *fixed* and *planned* multi-hop architecture for the extension of radio range and for the coverage of otherwise shadowed areas in B3G systems. We particularly focus on a scenario where the range of an AP is extended by four *Relay Stations (RSs)*, each having a receive antenna gain. Based on a set of assumptions on the technologies and paradigms used in such systems we quantify the achievable capacity and illustrate its inter-dependencies with some system parameters such as relaying strategy and RS receive antenna gain. We show how relaying helps to make the very high capacity of a single broadband access point available in a larger area than its original coverage, meeting the expected spatial distribution of the traffic demand more precisely. We propose and compare different mechanisms of relaying in the time domain for a planned infrastructure. Based on these mechanisms we show that the introduction of relay based deployment concepts can substantially increase the capacity of a single AP. We show based on a the assumed Manhattan scenario some promising deployment concepts that allow a spectral efficient wide area broadband coverage in such urban scenarios. Thereby we demonstrate some ideas how to exploit relaying inherent strategies by means of *coordination across Base Stations (BSs)* to increase the spectral efficiency of the relay based radio network deployment.**

***Index Terms*— Wireless Media System, Multi-Hop, Coordination Across BS, Radio Network Deployment Concepts**

I. INTRODUCTION

Future broadband radio interface technologies and the related high multiplexing bit rate will dramatically increase the traffic capacity of a single *Base Station (BS)*, so that it is deemed very unlikely that this traffic capacity will be entirely used up by the user terminals roaming in the cell. This effect will be amplified by the fact that future broadband radio interfaces will be characterised by a very limited range due to the very high operating frequencies which can be expected from such systems. Furthermore, future broadband radio interfaces will be characterised by high attenuation due to obstacles, leading to large areas that are shadowed from the BS.

A cost efficient and innovative solution is to trade capacity against range [1], [2] by partly utilising the capacity of an *Access Point (AP)*, i.e. a single “pico cellular BS”, by a number of *Relay Stations (RSs)*, which act as wireless BS to provide radio coverage in areas that are out of range or shadowed (no direct *Line Of Sight (LOS)* to the AP). The advantage over pico-cellular BSs is that the RSs do not need a wired network connection, which is the determining cost factor. This solution also appears very attractive since it is deemed unlikely that the high traffic capacity of a broadband AP will be used up by the user terminals roaming in its original coverage area [3]. The relaying concept applies to wide area as well as to short-range systems. An extensive discussion of this system concept, called *Wireless Media System (WMS)*, can be found in [4]–[6].

We use the following terminology:

Access Point (AP): An AP is a BS that is directly connected to the fixed network, either via fibre or via another air interface, e.g., Microwave LOS Radio, etc.

Relay Station (RS): A RS is *wirelessly* connected to an AP, having relay functions either in layer 3, 2, or 1. We distinguish between Fixed Relay Station (FRS) and Mobile Relay Station (MRS). A FRS/MRS appears to the terminals in its service area like a BS, while it appears like a terminal to its serving AP.

Media Point (MP): Both base station elements, the AP and the FRS, will be further referred to as Media Points.

In the following we restrict our investigations to FRSs that may be located at different places, e.g., on rooftops, walls of buildings or even lampposts. Such positioning has the side-effect that power supply is often available and advantageous LOS propagation can be arranged through proper planning.

The technology of relaying is not new, but in the past relaying was in most cases applied in conjunction with ad-hoc networking, which leads to dynamic network topologies and requires sophisticated routing strategies [7], [8]. An introduction into the whole area of multi-hop transmission in wireless networks, including the introduction of a clear terminology, is provided by Yanikomeroglu [9].

In this paper, the potential of relaying technologies for the use in mobile broadband systems with a *fixed infrastructure* is discussed. Some results already exist in this field as described by N. Esseling et. al. in [10] for HiperLAN/2. Their results are based on existing systems originally designed to work in single-hop mode.

The scenario our analysis is based on is described in Section II. In Section III the parameters and their impact on performance and cost of a multi-hop based system are discussed briefly, before giving an introduction to time domain forwarding techniques (Section IV) and their impact on the capacity (Section V). Based on these forwarding techniques some innovative radio network deployment concepts are shown in Section VI that allow a cost- as well as spectrum-efficient wide area broadband radio coverage. Section VII concludes our paper.

II. Scenario and Modelling

The investigated multi-hop system uses the same Orthogonal Frequency Division Multiplexing (OFDM) modem as used by HiperLAN/2, IEEE 802.11a or the W-CHAMB system [8]. Link level simulation results [11] for the Packet Error Rate (PER) as a function of the Signal to Noise Ratio (SNR) from a 5 GHz HiperLAN/2 system with 20 MHz channel bandwidth have been used as a basis for the analysis. The throughput of the proposed multi-hop system has been calculated as physical layer throughput without considering protocol header overhead. Retransmissions from a Selective Reject ARQ (SREJ-ARQ) protocol are taken into account. Further we assume an optimal link adaptation allowing to operate always on the PHY-mode which delivers the highest throughput as shown in Fig. 1 by the fat dashed curve.

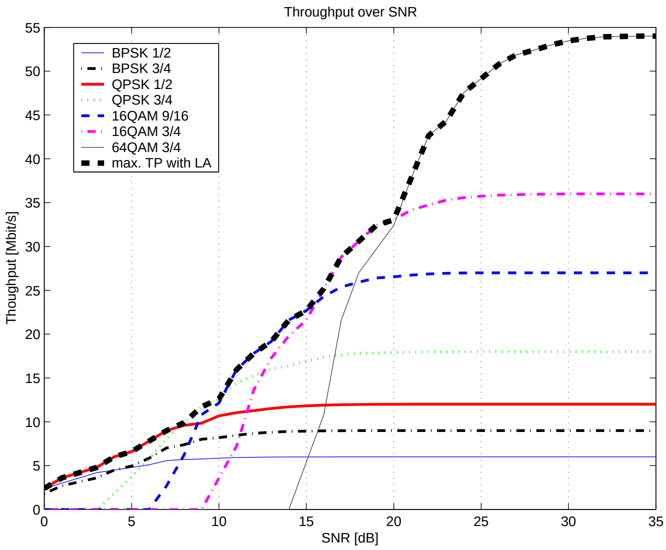

Fig. 1. OFDM Modem with optimal Link Adaptation [11]

In the analysis no interference from co-channel APs or FRSs is taken into account. The background noise was assumed to be -96 dBm. For calculating the relation between received SNR and distance from the transmitter we use the following simple path loss model [12]:

$$P_R = P_T \cdot g_T \cdot g_R \left(\frac{\lambda}{4\pi}\right)^2 \cdot \frac{1}{d^\gamma}. \quad (1)$$

P_R denotes the received signal power in Watt, P_T the transmitting power in Watt, g_T and g_R are the receiver and transmitter antenna gains, resp., λ is the wavelength of the transmitted signal, d is the distance between the transmitter and the receiver and γ is the pathloss coefficient. We assumed $\gamma = 3.5$ for non LOS (NLOS) conditions and $\gamma = 3$ for the LOS path in urban areas.

The FRS are assumed to use omni-directional antennas to serve their associated mobile terminals. AP and FRSs are transmitting on the same frequency, unless otherwise stated. Consequently, it is assumed that only one can transmit at a time. This principle is referred to as *time-domain relaying*.

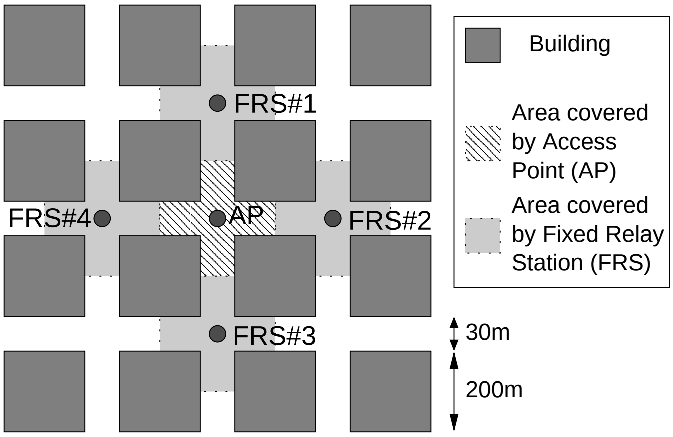

Fig. 2. 2-Hop Cell in Manhattan scenario

Fig. 2 shows a *2-Hop Cell* in the assumed Manhattan scenario [13]. The 2-Hop Cell is comprised by five *Sub-Cells*, one *Central Cell* covered by the AP and four *Relay Cells* covered by the FRSs. Each Mobile Terminal (MT) will be accessed with max. two hops. The streets in the assumed scenario are 30 m wide and the building blocks are sized 200 m x 200 m. Within this paper the Media Points (MPs) are located one in the middle of each intersection, i.e. 230 m apart.

III. Relaying Techniques and Parameters

In order to evaluate the feasibility of relaying concepts it has to be shown that the sufficient traffic performance can be maintained even at the end of each hop-chain. At the same time the relaying technology has to be as simple as possible to maintain the cost advantage.

The transmission power P_R has an impact on the range of each MP, either AP or FRS and on the available PHY mode and with it the throughput.

The use of antennas with gain seems only recommendable for the MPs due to cost and terminal size/complexity considerations. At the FRS the antenna gain plays an important role to increase the throughput. Due to the requirement that the FRS should look like a regular terminal to the AP, we assume that there is only a FRS receive antenna gain.

The pathloss coefficient itself cannot be influenced, but it depends on the scenario topology and the conditions on the transmission path. Due to employment of FRSs a "virtual" LOS condition between receiver and transmitter can be established almost everywhere, as the FRSs can be used to "look around the corner" and cover otherwise shadowed areas. Thus, we can assume a much lower mean path loss coefficient, compared to the mean path loss coefficient that is required to model usual transmission paths through or around obstacles.

The number of hops is a system-inherent parameter. It is obvious that a high number of hops increases the delay and affects the throughput. Furthermore the number of hops is directly related to the scenario geometry in order to benefit from the effect that a smartly positioned relay can cover otherwise shadowed areas.

Relaying can be performed in different domains, e.g., time-domain, frequency domain or code-domain. In the following relaying in the time domain will be investigated.

IV. Forwarding Scenarios in the 2-Hop Cell with Multiple FRSs

Obviously, the throughput decreases with an increasing number of hops [14]. Therefore in this section a *2-Hop Cell* with four FRSs is investigated as shown in Fig. 2.

The most simple case of forwarding is in the time domain with *equal time share* of the capacity [15]. The time frame of a system with four FRSs fed by one AP is shown in Fig. 3. For a better differentiation we will further refer to this case as *Case 1*. It can be seen that the time slot allocated to feed the MTs in the "Forwarding Cell" is split into two parts, one to transmit the data packet from the AP to the FRS (1^{st} hop) and one to transmit the data packet from the FRS to the MT (2^{nd} hop). The time required for the transmission on the first hop, $T_{Hop1} = T_{AP-FRS} = D_L/TP_{AP-FRS}(G, d_{AP-FRS})$, is mainly dependent on the antenna gain ($G = G_R + G_E$) and on the distance between the AP and the FRS, d_{AP-FRS}. TP_{AP-FRS} is the throughput available between the AP and a FRS. D_L is the length of the transmitted data packet.

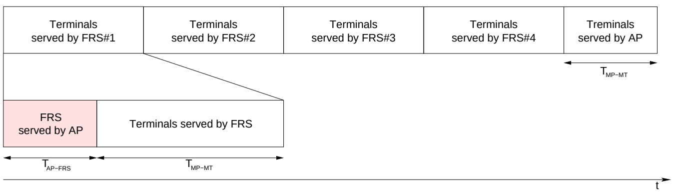

Fig. 3. Case 1: Time frame for simple time-domain relaying

Obviously, the solution shown above is very inefficient. Therefore, the overall capacity of the 2-Hop cell can be enhanced by exploiting the spatial independency of some of the "Forwarding Cells". Spatial independency in this case means that the cell areas of two or more FRSs are fully shadowed from each other as shown in Fig. 2 for, e.g., FRS#1 and FRS#2 or FRS#2 and FRS#3, etc. In the case of spatial independent "forwarding cells" neither, e.g., FRS#1 nor any MT in the cell of FRS#1 will cause any interference to the cell of FRS#2 and vice versa. This allows to exploit space division for these two "forwarding cells" resulting in a time frame as shown in Fig. 4. Now two of the four FRSs can transmit in parallel at the same time. This approach, named *Case 2*, is obviously only possible in a planned infrastructure and has to be adapted individually for each scenario. A fact that is true also for the cases shown below. More sophisticated cases including the use of more than one carrier frequency have been investigated in [14].

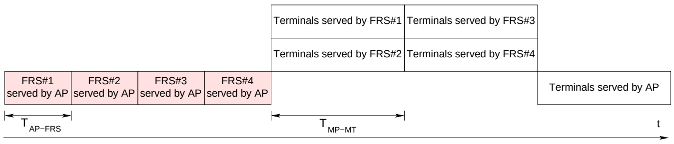

Fig. 4. Case 2: Time frame with 2x2 spatial independent "forwarding cells"

V. Capacity

To show the gain of the introduced relaying concepts the capacity of an AP feeding the 4 FRSs was calculated by means of the following formula as given in Eq. 2 [15]:

$$C = \frac{5N_{sc}}{\sum_{j=1}^{N_{sc}} \frac{1}{TP_{AP-MT}(d_j)} + 4 \cdot \sum_{j=1}^{N_{sc}} \frac{1}{TP_{FRS-MT}(d_j)}} \qquad (2)$$

N_{sc} denotes the number of users in each of the 5 sub-cells, either forwarding cell or central cell. d_j denotes the distances of uniformly distributed users to the next MP.

In Fig. 5 the capacities of the different cases of forwarding as introduced in Section IV are shown over the antenna gain available between the AP and the FRSs. The capacity shown is always the capacity of one AP, feeding the related FRS, i.e. the capacity of the whole 2-hop cell, as the whole traffic is going through the AP. As reference the capacity of an AP without FRS is given as a dashed horizontal line. The pathloss coefficient was set to $\gamma = 3$ for the connection between AP and FRS and $\gamma = 3.5$ for the NLOS connections of MT and MP. The transmission power was set to 20 dBm. It was further assumed that the users are equally distributed in the cell with a density of 0.1 user per square meter. To calculate the capacity the covered area was divided into circular areas containing the same number of users.

Naturally, the capacity of the AP increases in all relaying cases with an increasing antenna gain. It is very interesting to see that the capacity of *Case 2* is exceeding the capacity of a single AP already with an antenna gain of around 7 dBi. This is possible due to the effect that an increased number of users can be served with high data rates from the AP's point of view. Even the capacity of *Case 1* comes close to the capacity of the single AP, which means that the time spent to feed the FRSs is quite low compared to the time required to feed the MTs. This results in a capacity gain for a system with 16 dBi antenna gain and operating as proposed for *Case 2* of 1.3 Mbit/s which is a gain of 35 % compared to a system without FRSs.

VI. Multi-Hop Radio Network Deployment Concepts

The new cell layout requires new radio network deployment concepts that take the structure of the "multi-hop cell" and the inherent characteristics of the proposed forwarding techniques (see Sec. IV) into account.

A. Basic Multi-hop Cell Cluster

Assuming that all *multi-hop cells* in a contiguous area operate independent from each other, i.e., there is no coordination

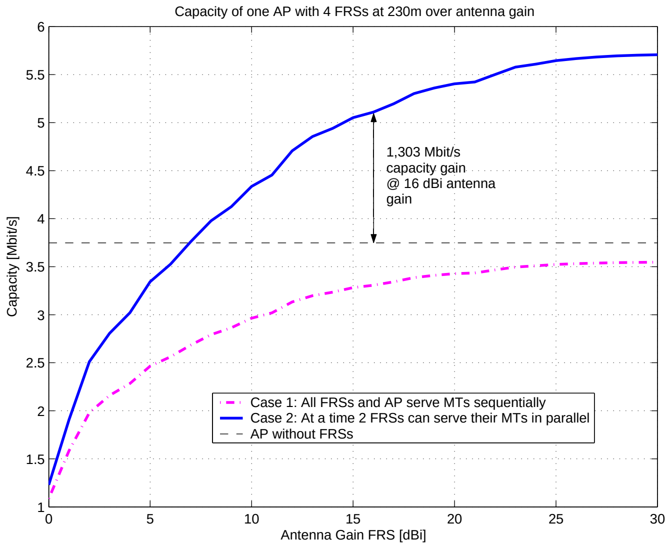

Fig. 5. Capacities of AP feeding 4 FRS 2-Hop cell vs. antenna gain for different relaying techniques

between the multi-hop cells, then three carrier frequencies are required to allow all multi-hop cells to operate in parallel, as shown in Fig. 6. The minimum distance of two co-channel interferers within this scenario is 230 m. In this case the maximum interference experienced by the MT is -109.1 dBm, assuming $\gamma = 3.5$ and a transmission power of 20 dBm. To calculate the interference between two FRSs $\gamma = 3.0$ is assumed. With a minimum distance of 460 m between two co-channel FRSs the interference power can be calculated to -99.9 dBm.

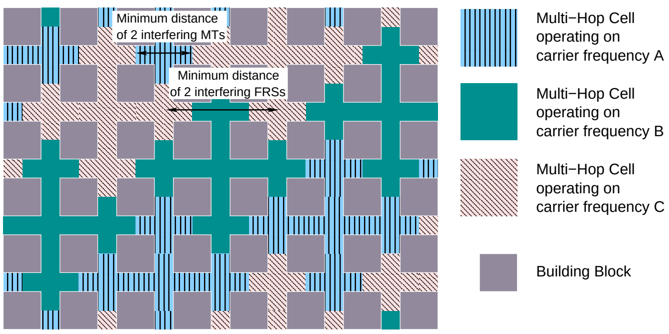

Fig. 6. Cluster of independent 2-Hop Cells consuming 3 carrier frequencies

B. Single Carrier Frequency with coordination across BS (Type I)

As described in Sec. IV not all MPs of one "multi-hop cell" are active at the same time. Due to the relaying in the time domain some time is required to feed the FRSs. This characteristic can be exploited in a way that allows a radio network deployment based on only one carrier frequency.

To achieve such a radio network deployment based on one carrier frequency a well defined *coordination across multi-hop cells* is required. This means that the time frames of the adjacent cells have to be synchronised in a way that the AP of *cell A* feeds its FRS and MTs at the same time when the FRSs of *cell B* serve their MTs as shown in Fig. 7. The figure shows that there are two groups of "forwarding cells" with a synchronised transmission of their APs and FRSs.

As illustrated in Fig. 7, this coordination across BSs means that the AP of cell A is active (including the serving of the related FRSs and its MTs) at the same time when the FRSs of cell B serve their terminals.

Fig. 8 shows how a cluster with one carrier frequency looks like in the assumed Manhattan scenario. The different colours (grey tones) illustrate the two different cell groups. The cells of one group have in common that their APs transmit at the same time as well as their FRSs. The pattern of the sub-cells shows whether the AP or FRSs transmit on *time slot X* or *time slot Y* according to Fig. 7.

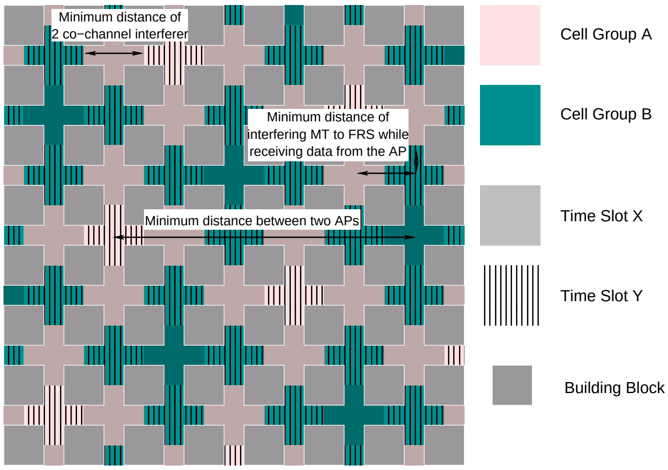

Fig. 8. Cluster with one carrier frequency and coordination across BS (Type I)

The co-channel interference between two MPs with the minimum distance of 460 m, 20 dBm tranmission power and $\gamma = 3.0$ can be calculated to -106.3 dBm, whereby a channel is determined by the time slot ("X" or "Y"). For two co-channel MTs the minimum distance is 230 m (see Fig. 8. With $\gamma = 3.5$ and 20 dBm transmit power this results in the same maximum interference of -109.1 dBm as for the scenario without coordination across BS.

Furthermore, the FRS can experience an interference from the MTs or FRS of adjacent cell while receiving data from its AP. But, due to the directional antenna at the FRS it can be assumed that the interfering signal will be received with a significant attenuation. Assuming a loss of 10 dBi the interference experienced by an interfering MT located in the adjacent cell direct to the border of the interfered sub-cell will be -108.6 dBm ($\gamma = 3.5$). The FRS of the adjacent cell would cause an interference of -107.3 dBm with $\gamma = 3.0$, a distance of 230 m, and also 10 dBi antenna loss.

C. Single Carrier Frequency with coordination across BS (Type II)

The "One Frequency Cluster" with coordination across BS as shown in the last section is not optimal as the time an AP

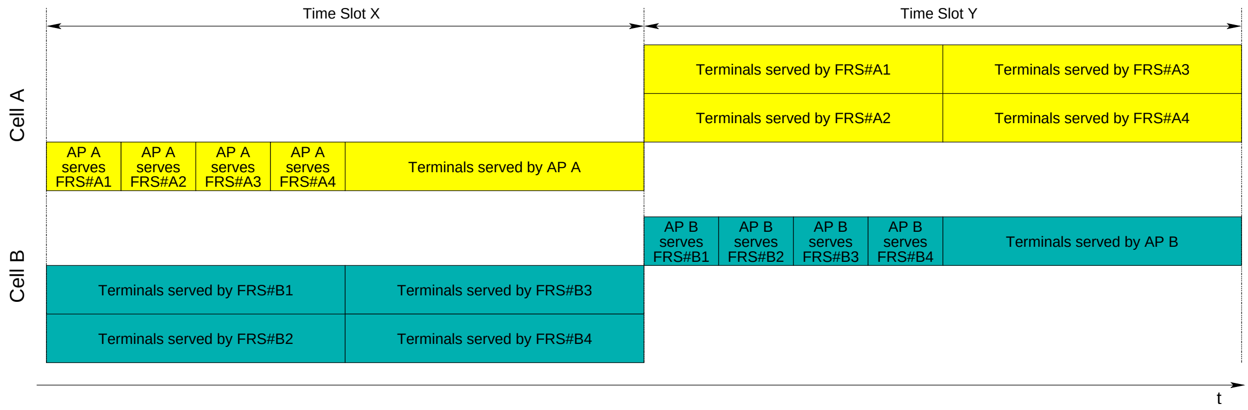

Fig. 7. Synchronised Forwarding Time Frames with Coordination across BS (Type I)

needs to feed its four FRSs might not be the same as the time the FRSs need to serve their MTs. This means that time and therewith capacity is wasted either during the feeding of the FRSs or during serving the MTs.

This can be avoided if all APs always feed their FRSs synchronised on the same time slot (*Time Slot F* in Fig. 9), which is possible as the APs of the different "Multi-Hop Cells" in the given scenario can not interfere each other because of the minimum distance between two APs of at least 1150 m (see Fig. 8). This means that only the FRSs have to be coordinated in a way that they don't interfere each other. Having a look at the structure of this forwarding mode *Case 2* (see Sec. IV) it can be seen that the FRSs of one "multi-hop cell" are grouped into two spatial independent groups of two FRSs each plus a time slot where the AP serves its MTs.

Therefore four time slots ("F", "X", "Y", "Z") are distinguished as shown in Fig. 9, whereby in "time slot F" all APs feed their FRSs. Applying this coordination scheme the scenario can be covered with one carrier frequency again, but now a minimum distance of at least 460 m between two co-channel interferers can be achieved.

Performing the same calculations as the for the previous deployment concept it results that the maximum interference of -111.6 dBm will happen between two co-channel MPs with a distance of 690 m and $\gamma = 3.0$.

D. Advantage of the Relay Based 1-Frequency Cluster

Due to the use of only one carrier frequency in the case of coordination across BSs two carrier frequencies are gained compared to the case without coordination across BSs or without relaying at all, i.e. one AP at each intersection. Therefore a capacity gain of about factor 3 can be achieved by increasing the channel bandwidth by adding two more carrier frequencies.

It is known that the biggest part of the radio network deployment costs are caused by the connection of the BS to the fixed network. These costs would be reduced to one fifth by the use of FRSs in the assumed Manhattan scenario, if we assume that otherwise every FRS would be replaced by an AP leading to five APs instead of one AP plus four FRSs. But on the other side it is likely that the FRS hardware itself is slightly more expensive than the AP hardware as the FRS are equipped with specific antennas allowing to have an antenna gain. For an example calculation the following assumptions were made:

- The costs of an AP ($Cost_{AP}$) are split into hardware cost ($Cost_{APHW}$) and costs for the (fixed) connection to the backbone network ($Cost_{BC}$):

$$Cost_{AP} = Cost_{APHW} + Cost_{BC} \tag{3}$$

- We assume that the share of the AP hardware cost is x [%]:

$$Cost_{APHW} = x \cdot Cost_{AP} \quad Cost_{BC} = (1-x) \cdot Cost_{AP} \tag{4}$$

- The costs of the FRSs ($Cost_{FRS}$) are only hardware costs which are assumed to be higher than for the AP due to the directed antennas. This is expressed by the factor $y > 1$:

$$Cost_{FRS} = y \cdot Cost_{APHW} = x \cdot y \cdot Cost_{AP} \tag{5}$$

Based on these assumption we can calculate the fixed costs for one "multi-hop cell" in the Manhattan scenario of Fig. 2 to

$$Cost_{mhcell} = 4 \cdot Cost_{FRS} + 1 \cdot Cost_{AP} = (1 + 4 \cdot x \cdot y) \cdot Cost_{AP} \tag{6}$$

Thereby $x \cdot y$ denotes the cost relation between the FRS and the AP. To achieve the a cost advantage for the multihop cell the inequation $x \cdot y < 1$ has to be fulfilled. This is very likely as the share for the connection to the fixed network can be assumed to at least 75 % ($x = 0.25$). With the assumption of $y = 1.2$ we achieve $Cost_{mhcell} = 2.2 \cdot Cost_{AP}$. For this basic approach we neglected the running costs which depend on time and traffic.

In comparison to the single hop scenario where five APs are required to cover the same area the costs for the "multi-hop cell" system are only 44 % of the cost of the single-hop solution.

VII. Conclusion

The introduction of a multi-hop component in future cellular broadband systems is a very attractive solution to the problem of having too much capacity available in a too small area,

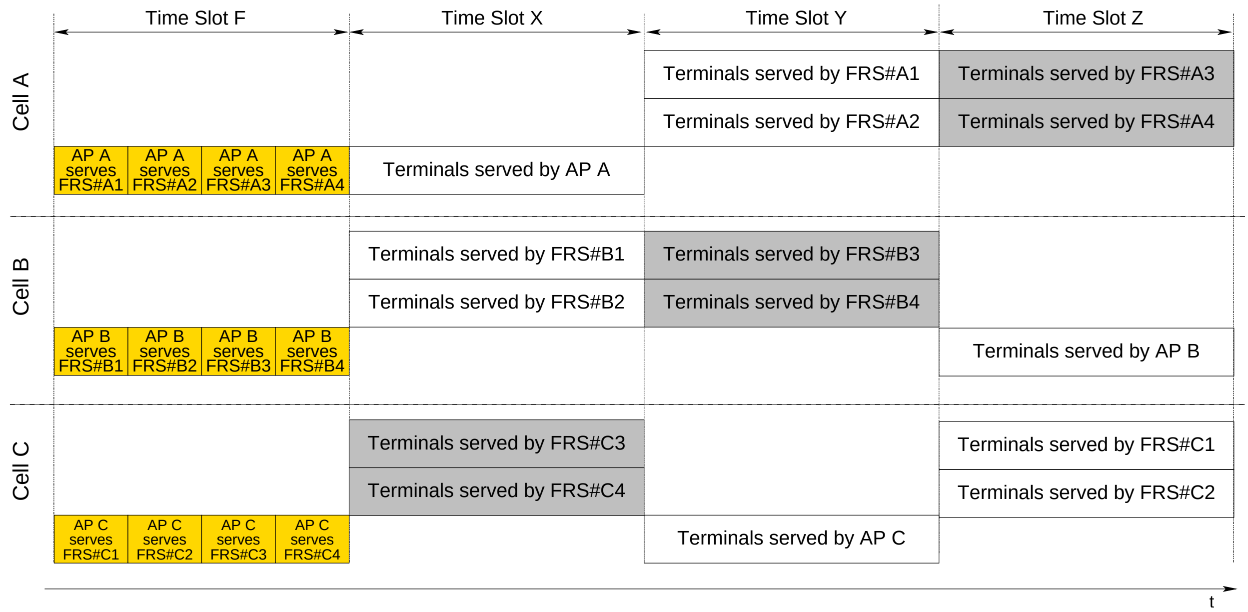

Fig. 9. Synchronised Forwarding Time Frames with Coordination across BS (Type II)

especially regarding urban scenarios, which are characterised by very short LOS paths.

On the other hand the multi-hop approach adds several additional dimensions to the parameter space that have to be explored in order to find optimised parameter sets. In this context there is the need for a general understanding of the impact the newly introduced system parameters have on the achievable traffic performance.

We introduced concepts to realise such relays by taking advantage of the spatial independency of sub-cells by otherwise disturbing obstacles and indicated the capacity gain of the proposed relaying method.

In this paper we have shown that infrastructure based relaying can be used to trade capacity against range in order to allow a cost efficient broadband radio network deployment. It was shown that new sophisticated deployment concepts can help to reduce the capacity loss of infrastructured relay based system to a minimum resulting in a cost advantage for the deployment employing cheap FRSs compared to a full AP including its connection to the fixed backbone network.

Although these analytical results are based on a very specific scenario and on ideal system assumptions, they point out the system inherent potential of relay based systems with fixed and planned infrastructure. For more realistic evaluation of the proposed relaying concepts system level simulations are required that also take some protocol issues into account as well as more sophisticated propagation models.

Further the economic advantages of relay based deployment concepts compared to a single hop solution have been shown by means a very basic cost calculation. These results based on rough estimations show impressively the potential of relaying in a fixed infrastructure.

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