Subcarrier Assignment for OFDM Based Wireless Networks Using Multiple Base Stations

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***Abstract*— In this paper we advocate the use of multiple base stations for providing wireless link to an OFDM–based terminal and thus obtain macro diversity, in particular *site diversity*. The wireless link to a terminal is defined through a subset of sub-carriers that is optimized in a greedy manner over the union of base stations. The wireless terminal is unaware of how many and which base stations are providing its allocated set of sub–carrier, which simplifies the terminal design. We give an analytical comparison of our approach to the conventional solutions. The results show that the proposed schemes with multiple base stations can outperform the single base station case, while keeping the complexity of the wireless terminal unchanged. We further evaluate our schemes by considering minimize signalling over the air interface.**

I. Introduction

The initial motivation to use Orthogonal Frequency Division Multiplexing (OFDM) in wireless networks was to combat multi–path and increase the spectral efficiency. In the subsequent developments, adaptive multi–modulation in combination with coding has been introduced, such as in IEEE 802.11a. In all those approaches, all sub–carrier of the systems are assigned to a *wireless terminal (WT)* for a given time. Recently, the dynamic subcarrier scheduling mechanisms gained a lot of interest [1], [2]. Their main motivation is to exploit the possibility to assign sub–carriers among terminals according to their quality. Obviously, such approaches leads to good results, but on the other hand they require signaling between *base station (BS)* and WTs. To the best of our knowledge, all previous approaches are based on the same architecture, namely one BS serving multiple wireless terminals.In this paper we advocate a new framework using multiple BSs serving each WT in a cooperative manner. The BSs agree beforehand on optimal sets of sub–carriers to send data to the WT. As a result, each sub–carrier is sent by exactly one BS, chosen in greedy manner. Since a WT is assigned a fixed set of sub–carriers, the cooperation of the BSs is transparent for the WT. Clearly, advanced coding schemes on the different sub–carriers can be used as in [3]. However, our scheme does not require any complex decoding schemes at the terminal side, which is in favor of the utilization of *low complexity terminals*.

In single–frequency systems [4] it has been proposed to transmit from several BSs simultaneously while limiting the delay between the signal from these different BSs. This allows the various signals to be handled as multi–path delay and such attained receive diversity enhances the performance. In contrast to this, in this paper the BSs transmit on mutually orthogonal sets of sub–carriers, meaning that a sub–carrier is only used by one BS. Such operation enables geographical frequency reuse and results in higher spectrum efficiency. To introduce our approach, consider the case where one BS is communicating with only one WT. Communication takes place using the channel available for BS1 and the quality of the sub–carriers may vary depending on the channel conditions. A performance increase can be obtained by using two BSs to communicate with the WT and selecting the the optimal subset of available sub–carriers based on the link quality. In order to do this, a new network entity to control the transmission of the BSs is introduced, the so called Inter–Base Station Sub–carrier Selection Unit (IBSSU). The IBSSU is used to coordinate the sub–carrier assignment of H BSs communicating simultaneously with the same WT.

Each BSi transmits on a subset of sub–carriers A_i, such that the sub–carriers assigned to WTj is $A_{WT_j} \subset A_1 \cup A_2 \cup \cdots \cup A_H$. The subset assignment is done based on the sub–carrier quality, such that it optimizes the system throughput. The subsets $\{A_{WT_j} \cap A_i\}$ for all i are chosen to be mutually orthogonal and WTj remains unaware of the exact number of BSs involved in the communication through A_{WT_j}. Therefore, no complex combining of different signals is required within the terminal. However, WT should estimate the phase offsets of the various transmitters and this is done in the channel estimation phase based on the pilot symbols in the preamble. This means that the preamble and pilot symbols should be designed such that the terminal is able to resolve the different channels between BS and the WT. Additionally they should be designed such that the IBSSU is able to select the appropriate sets of sub–carriers. We will introduce our approach and show the potential by comparing it with other scheduling schemes. A solid performance evaluation is provided through analysis and simulation.

II. System Model

Let us consider an OFDM–based wireless network which uses BSs to communicate with $J \geq 1$ WTs. A cell is the total coverage area of the $H \geq 1$ available BSs. Let the total number of available sub–carriers be N. The received signal strength from all BSs is assumed to be equal, which implies application of a power control scheme. Note, that even if this assumption does not hold, the approach is still valid. The WTs are connected to the BSs by assigning sub–carriers to the WTs and the assignment can be static or dynamic. Each sub–carrier reaches a WT with a certain signal to noise ratio (SNR). We can define a state for each sub–carrier to be the SNR for that sub–carrier at the WT. If we consider the *binary channel model*, the sub–carrier can have state 0 (low SNR and no communication possible between the BS and WT) and 1 (highest modulation and best communication possible). More generally, there can be intermediate states between 0 and 1 and in such case the used model is called a *M–ary model* (with M the number of different states) as in [2].

We define the *sub–carrier vector weight* σ as the sum of all the individual sub–carrier states at the WT. With this quality measure there is a linear relation between a state (corresponding to certain SNR) and the possible throughput. We still use the linear model to compare the different assignment schemes. We define the *normalized sub–carrier vector weight* w_n as the sub–carrier vector weight divided by the number of received sub–carriers. So, when the state of sub–carrier number n is S_n:

$$w_n = \sigma / N = \sum_{n=1}^{N} S_n / N \qquad (1)$$

III. Assignment with Binary Channel Model

In this section we use the binary channel model and the probability that a sub–carrier has the state 1 at the WT is P_g. Similar scenario, but for one instead of multiple BSs is described in [1]. This section compares the quality, in terms of sub–carrier vector weights as well as the complexity of three different schemes: Static Assignment Static Receiving (SASR), Dynamic Assignment Static Receiving (DASR), and Dynamic Assignment Dynamic Receiving (DADR).

A. Static Assignment Static Receiving (SASR)

The SASR scheme is the simple and does not achieve side diversity. Each WT gets a fixed set of $\frac{N}{J}$ sub–carriers, e.g. WT 1 gets sub–carrier $1 \ldots \frac{N}{J}$, WT 2 gets sub–carrier $\frac{N}{J} + 1 \ldots \frac{2N}{J}$ etc. Furthermore, each BS gets a fixed set of sub–carriers assigned, no sub–carriers are assigned twice and all sub–carriers get assigned. Hence, in the SASR case the total sub–carrier weight of all the users together will be $\sigma_{SASR} = N \cdot P_g$.

B. Dynamic Assignment Static Receiving (DASR)

The DASR scheme has more flexibility in assigning sub–carriers to BSs. As in SASR, the WT is assigned a fixed set of sub–carriers. But in this case the BSs can communicate with each other about which BS should provide which sub–carrier. As BSs are usually wired inter-connected, the inter–BS signalling in this case is not an issue. We assume that the BSs are able to determine a division of sub–carriers in such a way that the best possible connections are established. In this case the probability that a WT receives sub–carrier n in a good state, is the same as the probability that at least one out of the H BSs can send this sub–carrier in a good state to this WT. So, the total sub–carrier weight of all WT is $\sigma_{DASR} = N \cdot \left[1 - (1 - P_g)^H\right]$ and $w_{DASR} = \left[1 - (1 - P_g)^H\right]$.

C. Dynamic Assignment Dynamic Receiving (DADR)

The DADR scheme assumes total flexibility in assigning sub–carriers to BSs as well as assigning sub–carriers to WTs. Each WT still gets N/J sub–carriers assigned, but it is not predetermined which set of sub–carriers is assigned to a WT. In this way an optimal set of sub–carriers can be allocated to each WT. Further, just as in the DASR case, the BSs can communicate with each other about the assignment of sub–carriers to the different BSs. In DADR the probability that at least one out of the H BSs can send a given sub–carrier to a WT in a good state is determined. This probability is already shown in the DASR case and is $P_{gh} = \left[1 - (1 - P_g)^H\right]$.

Now we have transformed the H BSs into one BS with a higher P_g. So, to determine w we have to determine the sub–carrier vector weight in the scenario of one BS and multiple WTs. This case is discussed in [1], [2] and has the following approach. The BSs choose N/J sub–carriers towards the first WT out of the total N sub–carriers. According to this, for the second WT the BSs will then have to choose N/J sub–carriers out of the $N - N/J$ remaining sub–carriers. This process continues until the last terminal, where there are exactly N/J sub–carriers left. To determine the expected sub–carrier vector weight we have to determine the sub–carrier vector weight for each node. The expected sub–carrier vector weight for each WT consists of two parts, w_p and w_h. For w_p only good sub–carriers are assigned to this WT, and for w_h bad sub–carriers are assigned to this WT as well. If v is the WT number:

$$w_p = \left(1 - \sum_{i=1}^{N/J-1} \binom{(J-v+1)N/J}{i} (p_{gh})^i \cdot (1 - p_{gh})^{(J-v+1)N/J-i}\right) \cdot N/J$$

$$w_h = \sum_{i=1}^{N/J-1} \binom{(J-v+1)N/J}{i} (p_{gh})^i \cdot (1 - p_{gh})^{(J-v+1)N/J-i} \cdot i$$

The total sub–carrier vector weight will be the sum of all these vector weights:

$$w_{DADR} = \frac{\sigma_{DADR}}{N} = \frac{\sum_{v=1}^{J} w_{p,v} + w_{h,v}}{N} \qquad (2)$$

D. Evaluation of the Schemes with Binary Channel Model

In Figure 1 the results for the different scheduling schemes for $P_g = 0.7$ is given . The DADR scenario is shown for different number of WTs. This is done to show the different behavior of this scheme for different numbers of WTs. The other schemes do not behave differently for different numbers of users, because predefined sets of sub–carriers are assigned to them, that can not be changed later on, so only one line is shown for these scenarios. In the DADR case it is possible to divide the sub–carriers in any possible way over the different WTs. When there are more WTs available it is more likely

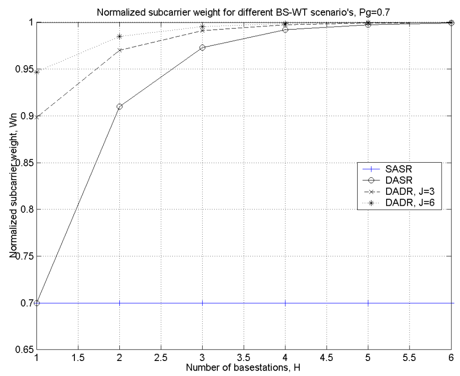

Fig. 1. The normalized weight of all WTs, $P_g = 0.7$, and for different scenarios

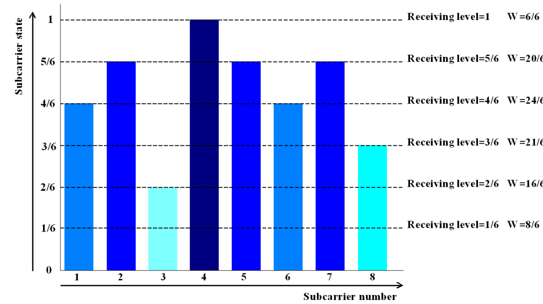

Fig. 2. An example of choosing one modulation type for all sub–carriers of a node, with the total sub–carrier vector weight of the node

to find WT that can get good sub–carriers assigned than when there are less WT available, so in this case σ depends on the number of WTs. Although the DADR case delivers the best results it should be pointed out that this scheme it introduces many difficulties in practical channel estimation schemes. With static receiving schemes, so SASR and DASR, the base stations can always get channel estimate for the assigned sub–carriers. For dynamic receiving the base stations should, in principle, have channel estimation for each WT over all available sub–carrier so as to make optimal assignment of N/J sub–carriers. Clearly in this case we have to provide a scheme for sharing the uplink transmissions of WTs over all sub–carriers. This complexity might reduce the possible throughput. In Figure 1 we can see that for three BSs or more the DASR and the DADR scheme deliver the same connection quality. These results all assume a binary channel model. In the next section the same investigations are done for a M–ary channel model as well.

IV. Assignment with M–ary Gaussian Channel Model

In the previous sections the advantage of assigning certain sets of sub–carriers to BSs and WTs is shown. In this way a node receives an optimal set of sub–carriers, which means that for each individual sub–carrier the best possible modulation and coding is used. Depending on the chosen scheduling scheme, the signalling of the modulation and coding type of each sub–carrier to a node has to be taken into account. A possible way to decrease this signalling is to use one modulation and coding type for all sub–carriers of a node (this requires one signalling information in case the channel condition change). The disadvantage of this approach is that there are sub–carriers which could use a better modulation and coding than the one used. Another disadvantage is that there are sub–carriers which can not communicate at the chosen modulation and coding type and they are not used at all for communication. The big advantage is that only one modulation type has to be signalled to each node. The optimal receiving level that state corresponding to the modulation and coding resulting in the highest sub–carrier vector weight.

To determine the quality of this approach the binary channel model can not be used anymore, because the optimal receiving level would almost be the state $S = 1$ giving us misleading too optimistic results. Since the sub–carriers that are in a good state are the only ones who contribute to the sub–carrier vector weight. So to determine the connection quality we use a M-ary channel model. The possible qualities of a sub–carrier are now defined as M different discrete states. Each state has a weight $\frac{i-1}{M-1}$, with $i = 1 \dots M$. The probability of a terminal having a sub–carrier in a given state towards a node is determined using the Gaussian distribution. For each state the probability of occurring is determined using the mean and the variance of the channel. The probability of a sub–carrier being in state i or smaller is called $P(S \leqq i)$. A total number of J nodes, M states, N sub–carriers and H BSs is assumed.

An example of this approach is shown in Figure 2, where $N/J = 8$ and $M = 7$. The weight would have been $30/6$ when the optimal modulation per sub–carrier would have been used. We can see that increasing the receiving level first increases the sub–carrier vector weight and at one point the weight will decrease when the receiving level is further increased. So an optimal receiving level can be determined based on the states of the individual sub–carriers of a node. In Figure 3 it the maximum throughput is shown for each receiving level, for different number of BSs for a M–ary channel model with an equal distribution. In the next sections the normalized sub–carrier vector weights are determined for a M-ary channel model. The σ is determined for each assignment scenario that is discussed earlier and for both choosing an optimal receiving level for each sub–carrier and for the case where one common receiving level is chosen for a total set of sub–carriers of a node. It is always assumed that each node gets exactly N/J sub–carriers assigned. The derived equations all assume a Gaussian channel model but they are also valid for a M-ary channel model with an equal distribution.

A. Static Assignment Static Receiving

In case of Static Assignment Static Receiving ($SASR$) the connection quality (expressed in normalized sub–carrier vector weight) does not change with the number of BSs because it is predetermined which BS will send which sub–carrier. First the probability of a sub–carrier being in state n is determined: $P(S = n)$. Furthermore the probability of a sub–carrier being in state n or larger is determined: $P(S \geqq n)$. In case we choose the best possible modulation and coding for each sub–carrier the normalized sub–carrier vector weight will be:

$$w = \sum_{i=1}^{M} P(S = i) \cdot \frac{i-1}{M-1} \tag{3}$$

In case we choose the modulation and coding resulting in the highest σ for the total set of sub–carriers of a node the normalized σ will be:

$$w = \max_i \left[P(S \geqq i) \cdot \frac{i-1}{M-1} \right] \tag{4}$$

B. Dynamic Assignment Static Receiving

When we use Dynamic Assignment Static Receiving ($DASR$) we are able to choose the optimal BS for each sub–carrier. First the probability that the best quality (out of all the BSs) of a given sub–carrier towards a node is in state n or smaller is determined.

$$P(S_{\text{best bs}} \leqq n) = P(S \leqq n)^H$$

From this we can simply determine $P(S_{\text{best bs}} = n)$ and $P(S_{\text{best bs}} \geqq n)$.

Next the normalized σ is determined in case we choose the best possible modulation and coding for each sub–carrier:

$$w = \sum_{i=1}^{M} P(S_{\text{best bs}} = i) \cdot \frac{i-1}{M-1} \tag{5}$$

In case we choose the modulation and coding resulting in the highest σ for the total set of sub–carriers of a node the normalized σ will be:

$$w = \max_i \left[P(S_{\text{bs best}} \geqq i) \cdot \frac{i-1}{M-1} \right] \tag{6}$$

C. Dynamic Assignment Dynamic Receiving

When we use dynamic assignment dynamic receiving we are not only able to choose the best BS for each sub–carrier but also the best node for each sub–carrier. For each sub–carrier to be assigned there are equal or less nodes to choose from than the previous sub–carrier that was assigned because each node can only get N/J sub–carriers assigned. For each single sub–carrier (sc) to be assigned the probability that there are a remaining nodes to choose from is determined: $P(J_{sc}^{remaining} = a)$, with $a = 1 \ldots J$ and $sc = 1 \ldots N$. Next for each sub–carrier to be assigned the probability that the optimal connection is in state i or smaller is determined as follows:

$$P(S_{\text{opt,sc}} \leqq i) = \sum_{a=1}^{J} P(J_{sc}^{remaining} = a) \cdot [P(S \leqq i)]^{a \cdot H}$$

From this probability we can simply determine $P(S_{\text{opt,sc}} = i)$ and $P(S_{\text{opt,sc}} \geqq i)$.

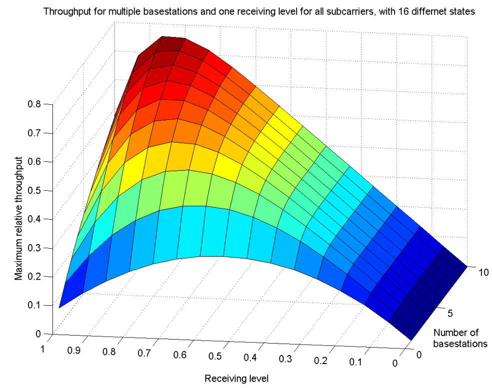

Fig. 3. The maximum relative throughput when choosing one receiving level for all sub–carriers, for a M-ary channel model with an equal distribution

Next the normalized σ is determined as follows in case we choose the best possible modulation and coding for each sub–carrier:

$$w = \frac{1}{N} \sum_{i=1}^{M} \sum_{sc=1}^{N} P(S_{\text{opt,sc}} = i) \cdot \frac{i-1}{M-1} \tag{7}$$

In case we choose the modulation and coding resulting in the highest σ for the total set of sub–carriers of a node the normalized σ will be:

$$w = \frac{1}{N} \max_i \left[\sum_{sc=1}^{N} P(S_{\text{opt,sc}} \geqq i) \cdot \frac{i-1}{M-1} \right] \tag{8}$$

In Figure 4 we can see what the normalized σ will be for the different assignment scenarios and for the two different receiving level scenarios. The vertical bars separate the different optimal receiving levels in the DASR case and next to the bars the optimal receiving level is shown. It can be seen that the DASR with an optimal receiving level for each sub–carrier performs comparable to the case of DADR with one optimal receiving level for all sub–carriers of a node. Furthermore it can be seen that for four BSs or more the DASR with one optimal receiving level for a total set of sub–carriers outperforms the SASR with an optimal receiving level for each sub–carrier.

V. Multicast Using Multiple BSs Serving Multiple Nodes

In the previous sections we have considered the case where several BSs send data to multiple nodes. In that case each node got its own unique data and its own unique set of sub–carriers. Now, multi–casting is assumed, where a group of users get the same content delivered. To get a quite realistic impression of the impact of sub–carrier assignments in case of multi–casting the M-ary Gaussian channel model is used to determine the σ. Each BS can reach each node with a given sub–carrier in a given state. But only one modulation and coding scheme can be used for each sub–carrier. So when one node can be reached in the best state and the others not it is probably not the best solution to use the highest modulation and coding.

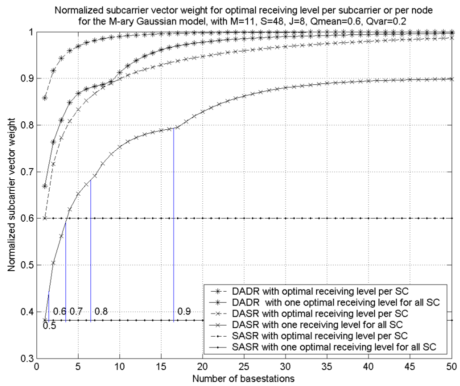

Fig. 4. The normalized sub–carrier vector weight when using a common receiving level per sub–carrier or per total set of sub–carriers of one node, using a M-ary Gaussian channel model

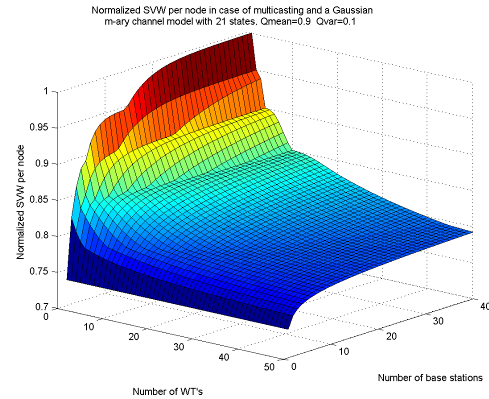

Fig. 5. The normalized weight per node in the case of multi–casting with multiple BSs and a M-ary Gaussian channel model

An optimal modulation and coding must be determined based on the different states a sub–carrier arrives from a BS to the different nodes. We call the number of nodes a base station can reach for a given state R. We call the probability that the BS with the best connection towards the total set of nodes for a given sub–carrier can reach exactly n nodes in a state i or higher $P(S \geqq i; R = n)$. If we choose to use the modulation and coding type according to state i the expected sub–carrier vector weight for this sub–carrier will be:

$$w_{m,i} = \sum_{n=1}^{J} P(S \geqq i; R = n) \cdot n \cdot \frac{i-1}{M-1} \quad (9)$$

So the optimal σ will be the one using that modulation and coding resulting in the highest σ:

$$w_m = \max_i \sum_{n=1}^{J} P(S \geqq i; R = n) \cdot n \cdot \frac{i-1}{M-1} \quad (10)$$

To determine $P(S \geqq i; R = n)$ we use the Gaussian probability distribution of the different states for a sub–carrier from each BS to each node. First we determine the probability that a BS can reach exactly n out of the J WTs in a state i or higher as follows:

$$P^1(S \geqq i; R = n) = \binom{J}{i} P(S \geqq i)^n P(S < i)^{J-n+1} \quad (11)$$

Next the probability that there is at least one out of the H BSs that can reach n or more out of the J nodes in a state i or higher.

$$P^H(S \geqq i; R \geqq n) = 1 - (1 - P^1(\geqq i; R \geqq n))^H \quad (12)$$

From this probability $P^H(S \geqq i; R = n) = P(S \geqq i; R = n)$ can be easily determined and Equation 10 can be solved. In Figure 5 an example of this kind of sub–carrier assignment is given. As can be seen in Figure 5 the normalized sub–carrier vector weight decreases rapidly with an increasing number of nodes per multi–cast group. Increasing the number of BSs increases also the sub–carrier vector weight. Furthermore the change of the common receiving level can be seen very well. By increasing from one up to ten terminal(s) per multi–cast group, the common receiving level has changed five times.

VI. Conclusion

In this paper we advocate the use of multiple base stations to support wireless terminals. Different sub–carrier assignment schemes are under investigation. For low complex terminal design the static set of sub–carriers per terminal seems to be the most promising one as no additional signalling is needed. The increase of the channel quality is achieved by the use of multiple base station. In this paper we have shown the potential of different approaches for two different channel models. Our proposed architecture includes a new entity the so called IBSSU which will increase the complexity of the backbone network allowing less complex terminal design. But we want to note here, that the architecture can be changed in that way that only one BS with multiple antenna arrays is used to support our idea. As it has been shown the connection quality can be drastically increased using sub–carrier scheduling for multiple base stations and multiple wireless terminals. The cost for this gain is an potential increase in the signalling for the sub–carrier and the modulation used. We could show that the gain of multiple BS decreases or even vanish when multi–casting is used. We investigated an approach with a common receiving level for all sub–carriers of a wireless terminal which has the big advantage that a minimum of signalling is used.

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