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Frequenz 59 (2005) 7-8

Coverage Extension of WiMax Using Multihop in a Low User Density Environment

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Abstract – The usage of multihop transmission enables a cost efficient extension of the coverage of a base station (BS) especially in low user density environment. In this paper, a network consisting of BSs and fixed subscriber stations (SSs) is considered in which the SSs are capable to act as relay stations (RSs). SSs connected to a BS forward the traffic to SSs at the cell border not having a direct link to a BS. The IEEE 802.16 (WiMax) standard defines a mesh mode enabling multihop transmission and communication between SSs. In this paper, the connectivity of a cellular multihop network based on IEEE 802.16 is analyzed. The maximum number of hops of a connection is limited to two. Even with a low density of SSs, the cell size can be increased. Increasing cell radius leads to a higher fraction of multihop connections and a higher usage of robust modulation and coding schemes (MCS) which causes a decreasing cell throughput.

Index Terms – Multihop, cellular network, wireless relaying, WiMax, IEEE 802.16

1. Introduction

The standard IEEE 802.16-2004 (WiMax) [1] defines an air interface of a broadband radio system supplying fixed and nomadic subscriber stations (SSs). A promising application of WiMax is its deployment in areas where wired broadband access is too expensive. Especially if a low density of SSs is expected, cost efficiency of the network will be improved by reducing the number of base stations (BSs), i.e., by increasing the distances between them. A too large distance between BSs means that a given area is not completely covered by BSs. Permitting a communication between SSs, a coverage extension of a BS is achieved by SSs acting as relay stations (RSs) as introduced in [2]. WiMax provides a mesh mode which allows communication between SSs [1].

In this paper, based on the mesh mode of WiMax a cellular multihop network is analyzed where the cell radius is chosen larger than the range of a BS. The number of hops in the analyzed network is limited to a maximum of two. Throughout this paper, each SS is assumed to have the technical capabilities to forward traffic of another SS. A SS currently forwarding traffic is called RS. Each SS with a direct link to a BS is called a potential RS. Only SSs act as RSs, there are no RSs deployed as part of the infrastructure. Therefore, the positions of the RSs are not determined in a cell planning process, but are random depending on the position of the SSs. A SS not within the range of a BS requires a potential RS within its range in order to establish a connection. A SS without direct link to a BS can establish a connection to a BS with a probability smaller than one [3], [4], [5]. The more SS are in the network the more probable a potential RS is found. Finding a potential RS is less probable in the case of a low density of SSs. In this paper, the connectivity depending on cell size and SS density is analyzed. Because WiMax defines several modulation and coding schemes (MCS), the effects of an extension of the coverage on the utilization of these MCSs and on the cell throughput is investigated.

In the following, the analysis of a TDD WiMax OFDM multihop network in a scenario with a low number of SS, each of them willing to act as RS, is presented. In Section II, the deployment of the multihop network is described and the medium access control (MAC) and the physical transmission of a multihop network in WiMax are shown. Section III gives the presentation of the scenario modeling followed by results of the connectivity of the cellular multihop network and of the throughput achieved by system level simulations. Conclusions are drawn in Section IV.

2. Cellular Multihop Network

2.1 Network deployment

A cellular multihop network is considered consisting of two types of stations: BSs and SSs. In each cell, one BS is positioned. Independently operating BSs are assumed, i.e., it is assumed that no common controller of BSs which synchronizes the network for interference reduction purposes exists.

The SS are fixed user terminals. SSs within the range of a BS are directly connected to this BS. Multihop transmission is used for coverage extension of a BS. The number of hops in the analyzed network is limited to a maximum of two because of two reasons. Firstly, more hops per connection cause a higher delay. For real time applications, the maximum delay is limited by constraints. Secondly, the bandwidth efficiency suffers with increasing number of hops. For interference avoidance, each radio resource in a cell is allocated not more than once. A multihop connection needs additional radio resources for repeating information on each hop, which decreases the bandwidth efficiency. On demand, each SS is willing to act as RS. A SS without a direct link to a BS establishes a link to a RS. Such a RS forwards the traffic of a SS from the SS to the BS in uplink and from the BS to the SS in downlink, respectively. In this paper, a multihop connection is only established if a direct link to a BS is not possible. Multihop is not used for throughput enhancement. Therefore, links between SS are only used to forward information from a SS out of range of a BS. Each SS only uses one connection to the BS, i.e., cooperative techniques are not considered. Representing the links between nodes of a cell as a graph, the connections have the topology of a tree.

2.2 Multihop Transmission in WiMax

The realization of multihop transmission using WiMax is described in the following. In [1] the MAC and physical layer of the mesh mode in WiMax is specified allowing communication between SSs. The mesh mode enables a connection over several hops and allows, among others, the network topology of a tree as described above. The mesh mode is incompatible to the specified point-to-multipoint mode which is only capable of single hop transmission and which has a lower signaling overhead than the mesh mode. Therefore, a proposal of a MAC layer enabling relaying is currently developed in the relay task group [6] of IEEE 802.16. Because the specification of multihop relaying is an ongoing process, the MAC and physical layer of the mesh

Frequenz
59 (2005)
7-8

mode specified in [1] is chosen to evaluate the performance of a cellular multihop network.

The wireless medium is shared by using TDMA. The frame structure is illustrated in Figure 1. A frame consists of an integer number N of OFDM symbols. An OFDM symbol consists of 256 carriers of which 192 carriers are used for control or data information and the rest as pilots and guard carriers. A frame is split into two sub-frames. The frame starts with a control sub-frame followed by a data sub-frame. The control sub-frame is used either as a network control sub-frame or as a schedule control sub-frame. The network control sub-frame is used periodically for network configuration. Due to its long period, the overhead introduced by the network control sub-frame can be neglected.

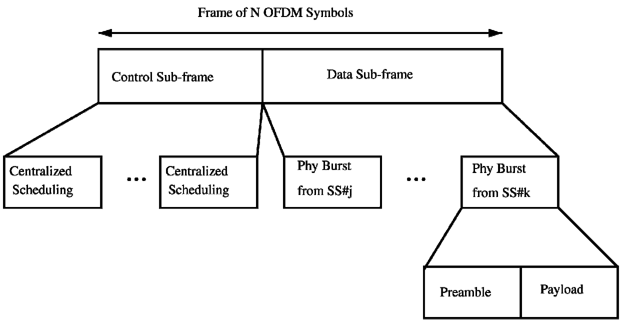

Fig. 1: Frame structure mesh mode.

For coordination of transmissions in the data sub-frame, a distributed and a centralized scheduling method are specified. In the following, only centralized scheduling is considered where resources are allocated by the BS and not by the SSs. Using centralized scheduling, a SS requests bandwidth from the BS it is assigned to. The BS grants resources to the SS. Scheduling messages are forwarded to the SS via a RS if a SS has no direct link to a BS. The length of the control sub-frame is an integer number N_C of OFDM symbols and a multiple of seven. N_C depends on the number of links in a cell. A calculation of the signaling overhead can be found in [7].

The N-N_C resources of the data sub-frame are shared by the SSs. The data sub-frame consists of physical bursts of variable size. A physical burst starts with a preamble, in general, of length of two OFDM symbols. Optionally, the length can be reduced by one symbol. The preamble is followed by the payload of the burst carrying MAC protocol data units (PDU). The receiver of a PDU is defined by a connection identifier in a MAC header. A burst may contain PDUs of several receivers. The payload is transmitted by the usage of a MCS_i, with $i=1,\ldots 6$. The modulation schemes and code rates of the MCSs are given in Table I. Depending on the link quality, a quadrature phase shift keying (QPSK) or a quadrature amplitude modulation (QAM) can be chosen. The error correction code consists of a concatenation of a Reed-Solomon and a rate-compatible convolutional code. The last column of Table I gives the minimum required signal to interference and noise ratio (SINR) γ_i for approximately error-free reception of a MCS_1 taken from [8].

Table 1: Modulation and Coding Schemes.

	Modulation	Code Rate	γ_i
MCS_1	QPSK	1/2	2.5 dB
MCS_2	QPSK	3/4	6 dB
MCS_3	16-QAM	1/2	9 dB
MCS_4	16-QAM	3/4	12 dB
MCS_5	64-QAM	2/3	16 dB
MCS_6	64-QAM	3/4	21 dB

3. Performance Results

3.1 Scenario Modeling

In the analyzed scenario, hexagonal cells are considered. The position of the SS follows a uniform random distribution. Simulation parameters are shown in Table II. A system with a total bandwidth of 10.5 MHz with a centre frequency of 3.5 GHz is assumed. Due to the TDD frame structure, a situation can occur in which a SS at a cell border is in receive mode while a nearby SS assigned to a neighboring cell is in transmit mode. If neighboring cells use same resources in such a situation, the SS in receive mode will suffer from strong interference. Therefore, a frequency reuse of three is necessary. According to [9], the wireless channel is modeled by a deterministic path loss model and a lognormally distributed random variable representing slow fading effects. Path loss model and standard deviation of the slow fading variable can be taken from Table II for the link between BS and SS and the link between SSs. Fast fading is not directly modeled on the system level, but part of the link level results.

3.2 Simulation Results of Connectivity

In this Section, the connectivity in the considered cellular multihop network is analyzed. The connectivity is described by an outage probability. The outage probability gives the portion of SSs in the total network which are not capable to establish a connection because these SSs are not within the range of a BS or potential RS.

Table 2: Scenario Parameters.

Parameter	Value
Number of cells wrapped around a torus	27
Centre frequency	5.5 GHz
System bandwidth	10.5 MHz
Reuse	3
Frame duration	20 ms
N	294
N_C	28
Transmit Power P_{TX}	35 dBm
Noise Power P_N	-100.5 dBm
Antenna type	omni directional
Path loss BS-SS [9] in dB	84.75+43.75 $\log_{10}(d[m]/100)$
Path loss S-SS [9] in dB	84.75+57.85 $\log_{10}(d[m]/100)$
Standard deviation [9] slow fading BS-SS	9 dB
Standard deviation [9] slow fading SS-SS	10.2 dB

The maximum cell is given size by the range of a two hop connection. The range of a BS and of a RS is limited by γ_1 of Table I which must be achieved at the receiver for the reception of a signal with lowest MCS, *i.e.*, MCS_1. Receiving no interference in ideal case, the minimum receive power $P_{RX,MIN}$ in dBm needed for a link is calculated by $P_{RX,MIN}=\gamma_1+P_N$ where P_N is the noise power at the receiver in dBm. For a given distance between two stations, the receive power is a random process because of the modeling of the slow fading by a random process.

Initially, the principle problem of connectivity in a cellular multihop network is described without the effect of slow fading. But slow fading is included in the simulation results given later. Neglecting slow fading, the maximum cell radius that can be achieved by a two hop connection is equal to the sum of the range R_{BS} of a BS and the range R_{RS} of a RS. Taking into account

Frequenz 59 (2005) 7-8

both path loss models of the BS-SS and RS-SS links in a link budget, the range of the BS is R_{BS} =1267m and the range of the RS is R_{RS} =682m in the modeled scenario, so that a maximum cell size of R_{MAX}=1949m is considered. If the channel between a BS and a SS provides a receive signal with strength larger than $P_{RX,MIN}$, the SS will be directly connected to the BS. Otherwise, the SS is connected to a RS in the case that a RS with a sufficient receive power $P_{RX,MIN}$ can be found. The area supplied by a BS shall be represented by a circle of radius R_{BS} with centre equal to the position of the BS. The area within the range of a SS looking for a connection to a BS shall be represented by a circle of radius R_{RS} with centre equal to the position of the SS. Then, a RS must be located in an intersection of the range of the SS and any BS. The nearer a SS is to a BS, the larger is the region where a RS can be located yielding a higher probability to find a RS. Notice that a RS needs not to be an active SS which generates own traffic while acting as RS.

The connectivity of the cellular multihop network is evaluated by means of system level simulations including slow fading. Because R_{BS} and R_{RS} are just estimates of the ranges neglecting fading, simulations are done for cell radii between 1000 and 2000m. In Figure 2, the outage probability is illustrated for different average numbers of SSs in a cell as a function of the cell radius. A comparison to a scenario in which only single hop connections are allowed shows that the usage of two hop connections enables a significant increase of the cell radius at an outage probability of, e.g., two percent. The outage probability is reduced when more SSs are available as RS.

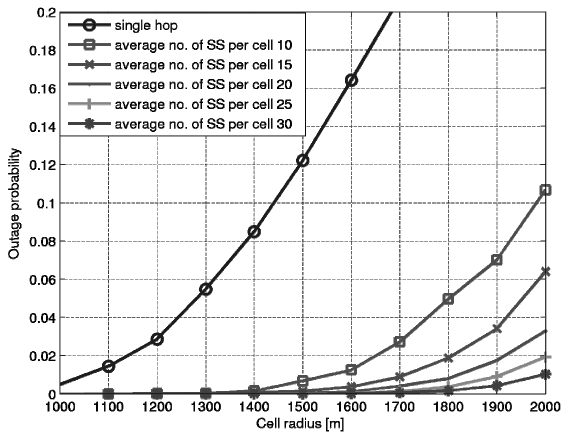

Fig. 2: Outage probability depending on cell radius.

3.3 Simulation Results of Throughput

In the following, the consequences of increasing the cell radius on the utilization of the MCS and on the cell throughput are shown in the modeled scenario for the downlink. For simplification, it is assumed that an active node generates as much uplink traffic as it demands downlink traffic, so that half of the resource of the data subframe are available for downlink transmission. No QoS constraint, e.g., no minimum data rate, is considered. The throughput performance of packet oriented systems depends on the applied scheduling algorithm. A simple centralized scheduling algorithm is considered in which resources are fairly allocated by the BS to all single and multihop connections in a cell. A link of a RS on which traffic of a two hop connection is forwarded is allocated more OFDM symbols proportional to the number of SSs supplied by the RS. All resources are in use to model a fully loaded system generating a maximum of interference. For relaying, a non-cooperative fixed decode-and-forward protocol is considered. A RS applies error correction to a received message, i.e., the message is reencoded and forwarded. A link adaptation and routing protocol with perfect channel state information is assumed. For two hop connections, the MCS is adapted to the weakest hop of the connection and keeps the same on the first and second hop. In situations in which a SS without direct link to a BS has the opportunity to choose between several paths to a BS, the connection is taken which allows the best MCS.

As a result of simulations, the distribution of the type of connections and the utilization of the MCS are presented to show the consequences of extending the cell radius on the downlink cell throughput. The fraction of single hop connections related to the total number of SSs is given in Figure 3 as a function of the cell radius. The fraction of single hop connections is independent of the number of SS in the network. The fraction of two hop connections is given by the portion of SS not being in outage and not having a single hop connection.

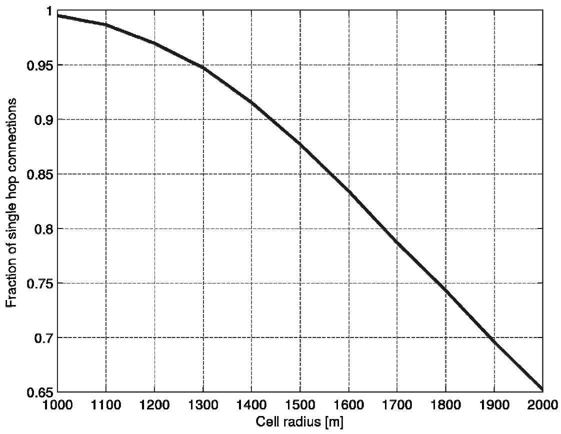

Fig. 3: Fraction of single hop connections depending on cell radius.

The utilization of the MCSs and cell throughput results are calculated for an average number of ten SS per cell where only 40 % of the SS are active, i.e., they transmit or receive own traffic. Figure 4 illustrates the utilization of a MCS for single hop connections in downlink as a function of the cell radius. The utilization of MCS_i is given by the denoted area between the plotted curves. The utilization of the MCS of the single hop connection is independent on the number of SSs in the network. With larger cell size, the fraction of robust MCS increases even if the cell size exceeds R_{BS}. For increasing cell sizes, a larger portion of resources are given to RSs and a smaller one to the BSs because of the applied fair scheduling causing a stronger interference.

Expanding the cell size, the fraction of single hop connections is reduced and the fraction of two hop connections increases. Figure 5 shows the utilization of MCSs for two hop connections as a function of the cell radius. For small cell sizes, predominantly high MCSs are used for two hop connections. Increasing the cell radius rapidly suppresses higher MCS so that for large cell size MCS_6 is almost vanished for two hop connections. Note that an increasing number of SSs improves the utilization of higher MCS on the two hop connections. Because of the higher probability of finding a RS, a SS without a direct link to a BS can possibly choose between several connections.

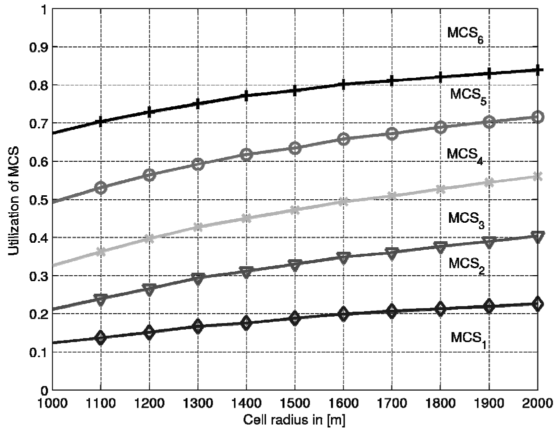

Fig. 4: Utilization of MCS on single hop connections depending on cell radius.

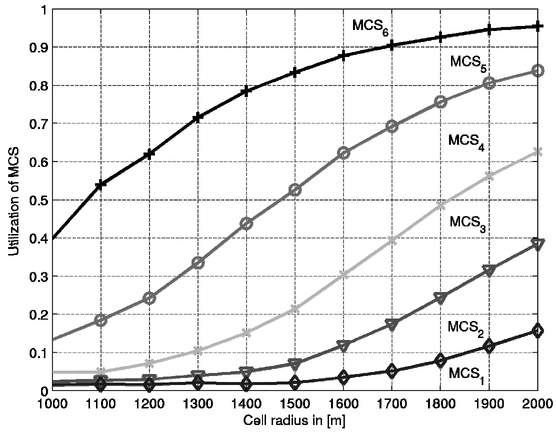

Fig. 5: Utilization of MCS on two hop connections depending on cell radius.

Considering all types of connections of a cell, an increase of the cell radius causes a degradation of the average downlink cell throughput as given in Figure 6. The average downlink cell throughput is reduced by roughly 40% if the cell radius is increased from R_{BS} to R_{MAX}. In larger cells, more robust modulation and coding schemes with lower spectral efficiency are used to compensate the larger path loss. Additionally, the average number of hops per connection rises, where two hops requires double amount of radio resources.

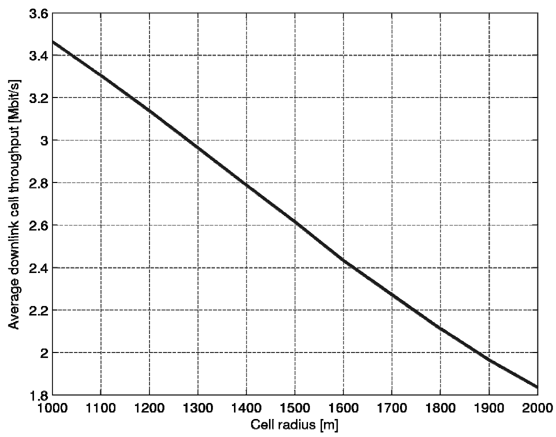

Fig. 6: Average downlink cell throughput depending on cell radius.

4. Conclusion

An extension of the coverage of a BS by using SS as relays has been analyzed by system level simulations assuming a low density of SS. Accepting a certain probability that a SS has no access to the system, cells can be expanded. An increased cell radius means reduction of the density of BSs and leads to a cost reduction of the network deployment. Since a larger cell radius causes a lower utilization of higher MCSs and because of additional resource requirements for a second hop, the maximum cell throughput decreases as shown for the case of the downlink.

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