Exploiting IEEE802.11n MIMO Technology for Cost-Effective Broadband Back-Hauling

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Abstract. The lack of affordable broadband Internet connectivity in rural areas, especially in emerging regions, is seen as a major barrier for access to knowledge, education or government services. In order to reduce the costs of back-hauling in rural regions, often without access to a stable power grid, alternative solutions are required to provide high-bandwidth back-hauling at minimal power consumption to allow solar-powered operation. In this paper, we show that cost-effective low-power IEEE802.11n (MIMO) hardware together with a single cross-polarized antenna can be a viable solution to the problem. Our study shows that up to 200 Mbps of actual throughput can be achieved over distances larger than 10 km while the power consumption of a typical forwarding node is well below 10 Watts (http://wiback.org/repeater) - suitable for a cost-effective solar-powered operation. Through theoretical analysis and extensive measurements we show that such a low-cost setup can be used to establish reliable long-distance links providing high-bandwidth connectivity at low latencies and consequently providing the capacity demanded by today's services - everywhere. Exploiting these findings we are in the process of extending existing fiber-based infrastructures in rural Africa with our Wireless Back-Haul (WiBACK) architecture.

Keywords: IEEE 802.11n · MIMO · Long-distance · Wireless back-haul

1 Introduction

Operators in rural areas often face the challenge to support the bandwidth and QoS demands of today's on-line service offerings. While in urban areas back-hauling capacity can be increased at relatively low costs via a wire-line infrastructure, in rural areas wireless technologies are often the only affordable means to establish back-hauling connectivity. Especially in emerging regions, the potential lack of access to a stable power grid is another crucial factor regarding the CAPEX and OPEX considerations of candidate technologies.

In such scenarios, back-hauling networks are often built based on commercial-of-the-shelf IEEE802.11 WiFi technology, to due its relatively high capacity and a low energy footprint. Managed by Wireless Mesh Network (WMN)-style protocols such architectures, for example our carrier-grade WiBACK[1] architecture,

[1] http://www.wiback.org

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offer the potential to reduce CAPEX and OPEX tremendously due to their self-configuration and self-management features, thus providing a resilient and fault-tolerant network [1–3].

Legacy IEEE802.11a technology typically supports a maximum effective data rate of approximately 30 Mbps [4], which can easily become a bottle neck in the network, especially if triple-play services are to be supported. The more recent IEEE802.11n standard [5] promises a tremendous increase of the actual throughput by introducing more efficient Modulation and Coding Schemes (MCSs), frame aggregation and Multiple Input Multiple Output (MIMO) support. The main focus of the IEEE 802.11n standard is rather short distance communication and many devices with the ability of using those advanced features can already be found in consumer electronic devices.

The topology of a typical WiBACK scenario, however, is based on point-to-point links with distances reaching from a few hundred meters up to several kilometers defining a completely different scenario as intended by the IEEE standard. In this paper we explore the applicability of IEEE 802.11n for long-distance WiFi links and therefore as an option to increase the overall capacity inside a WiBACK network. Our major focus is on exploiting the capacity gains introduced by the MIMO capabilities using a single cross-polarized antenna, which would allow to a very cost-effective design of multi-radio forwarding nodes.

The remainder of the paper is structured as follows. In Sect. 2 we introduce related work and briefly summarize the main concepts of IEEE802.11n and MIMO including upcoming challenges with long distance links. Section 3 describes our experiments with long distance 802.11n MIMO links and their results which we conclude in Sect. 4.

2 Related Work and Background

In [6] experiments with long distance MIMO links focusing on polarized antennas[2] are presented. Using .11n draft 2.0 and a maximum link distance of 700 m, they show that polarized antennas improve MIMO for long distance and a maximum throughput of 60 Mbps was reached. In [7] the authors show that even for long distance MIMO links high ranked channel matrices are possible. The focus in [8] is the definition of a model describing the coverage and capacity of a .11n cell based approach. In [9] similar considerations about 802.11n links were done however, their results differ from ours. The maximum throughput reached was 40 Mbps exploiting all 802.11n features over 1.8 km and they measured a significant gradual decrease over the link distance. This throughput decrease seems to be related to a low SNR rather than to the applicability of 802.11n features on long distance links. To the best of our knowledge, no prior research has investigated the maximum possible throughput of IEEE802.11n MIMO long-distance links (>10 km) using a single cross-polarized antenna while taking QoS considerations into account.

[2] And the influence of the “Keyhole Effect”.

2.1 Technology Enhancements of IEEE802.11n

Rather than summarizing the standard in general the purpose of the following section is to theoretically identify the main difference between .11a and .11n so previous knowledge about the concepts of WiFi is desirable. All following information are taken from the current standard itself [5] as well as [10].

Physical Layer. Regarding the main concepts of the PHY layer .11a and .11n use the same principles to ensure interoperability. However, 802.11n extends the concepts in every parameterizable value aiming at a throughput increase of the current maximum 54 Mbps as described in the following.

Although IEEE802.11a allocated a channel width of 20 MHz only 16.56 MHz are used divided into 53 subcarriers (0.3125 MHz each) with 48 of them containing data bits. IEEE802.11n exploits the 20 MHz more efficiently by adding two *additional* data *sub-carriers* on each side increasing the maximum physical throughput to $54\,\text{Mbps} * \frac{52}{48} = 58.5\,\text{Mbps}$.

To detect a limited number of errors after the transmission .11a use convolutional codes with a maximum coding rate of 3/4. With less redundancy, 802.11n introduces an *additional coding rate* of 5/6 increasing the maximum physical data rate to $58.5\,\text{Mbps} * \frac{4}{3} * \frac{5}{6} = 65\,\text{Mbps}$.

Intersymbol interference is an unwanted phenomena in telecommunications where one symbol interferes with subsequent ones. For IEEE802.11a one OFDM symbol last 4 μs consisting of 3.2 μs data and a guard period of 0.8 μs, .11n introduced the optional feature of a *shortened guard-interval* lasting 0.4 μs and decreasing the overall symbol duration to 3.6 μs and therefore increase the maximum throughput to $65\,\text{Mbps} * \frac{4}{3.6} = 72.2\,\text{Mbps}$.

To overcome the limits proposed by the Shannon-Hartley theorem, the most obvious move to increase the throughput is to use a wider communication channel, while .11a defines a maximum *channel width* of 20 MHz[3] .11n allows to double this capacity to 40 MHz. Two direct 20 MHz neighbor channels can be bundled to overall 116 OFDM sub-carriers (108 containing data) increasing the maximum physical data rate to $72.2\,\text{Mbps} * \frac{108}{52} = 150\,\text{Mbps}$.

All introduced enhancements in this sections apply equally to all lower 802.11n modulations as well and are, for the 802.11n case, called Modulation and Coding Scheme (MCS) labeled from zero to seven.

Medium Access Control Layer. After applying the high throughput enhancements to the physical layer, changes on the MAC layer were mandatory due to the poor scaling of throughput at the MAC layer, especially when using high physical data rates [10]. Some of the following MAC enhancement were already introduced by the IEEE802.11e standard nevertheless they are consistently extended for .11n.

Between every transmission a small period of time (SIFS - 16 μs) is added to ensure the receiver has the chance to sent an acknowledgement or other stations

[3] With the exception of the Atheros proprietary "Super-G" mode.

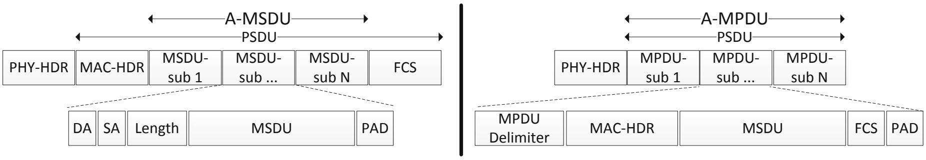

Fig. 1. Frame aggregation: A-MSDU and A-MPDU [11]

can apply for a transmission (back-off). Arbitration interframe spaces (AIFS) lead to the possibility of prioritizing traffic from different classes (i.e. voice over best effort) and Reduced Interframe spaces (RIFS - 2 μs) provide the possibility of a so called burst transmission (Fig. 1).

IEEE802.11n further increases the efficiency by surrendering inter-frame spaces between data frames leading to the main .11n MAC layer technique - *frame aggregation*. The standard distinguish between two different types of aggregation: the aggregate MAC protocol service unit (A-MSDU) and the aggregate MAC protocol data unit (A-MPDU) logically residing at the top (A-MSDU) or the bottom (A-MPDU) of the MAC layer [11]. The A-MPDU method aggregates completely formatted MAC frames including a MAC header for every sub-frame which consequently make the A-MSDU method more efficient. Both mechanisms share the same restriction that each sub-frame in one block has to share the same addresses and traffic class. For the A-MPDU case the *Block ACK protocol* efficiently confirms sub-frames through a bitmap to acknowledge or demand a retransmission.

Multiple Input Multiple Output. MIMO describes a system using a transmitter and receiver with multiple antennas communicating through a propagation environment [10]. Theoretically, MIMO promises an extraordinary increase in the capacity of wireless networks and has therefore drawn considerable attention in the last decade [7]. Although MIMO can be considered as a physical layer enhancements it is not limited to WiFi and a central issue in this report which justifies the approach in this separate section.

To understand the potential as well as the challenges of the MIMO signal transmission technique a further simplified communication channel model taken from [10] is given for a Single Input Single Output in Eq. 1 and for a 2×2 MIMO[4] system in Eq. 2.

$$y = h * x + z \tag{1}$$

$$\begin{pmatrix} y_1 \\ y_2 \end{pmatrix} = \begin{pmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{pmatrix} * \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} + \begin{pmatrix} z_1 \\ z_2 \end{pmatrix} \tag{2}$$

These equations may be used to describe each OFDM sub-carrier in the frequency domain. Different approaches can be found in [7,10,12]. In this model x describes the transmitted, y the received signal and z is Additive White Gaussian

[4] Two transmitting and receiving antennas.

Noise (AWGN). Variable h is defined as the channel fading coefficient, a complex scalar element representing the gain and phase of the channel usually modeled as Rayleigh fading. A simplified but here still sufficient approach is to define fading as the attenuation deviation affecting the signal. Deviations occurs for example by geographical conditions, the used radio frequency or multi-path propagation. For the MIMO case (2) h_{ij} describes the fading coefficient occurring for the transmission from antenna i to j. To extract the wanted information x from the received signal y the receiver needs to challenge two main tasks. First the coefficients h_{ij} needs to be specified which is for .11n realized by the so called pilot based channel estimation where predefined symbols are attached in the beginning of every OFDM frame. The second task is rather mathematical but explains the main challenge for MIMO well. To extract the information, the matrix H needs to be inverted [10] which is only possible if the matrix is non-singular ($h_{ii} \neq h_{ij}$).

$$x = \widehat{x} - z * h^{-1} \tag{3}$$

$$\begin{pmatrix} x_1 \\ x_2 \end{pmatrix} = \widehat{\begin{pmatrix} x_1 \\ x_2 \end{pmatrix}} - z * \begin{pmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{pmatrix}^{-1} \tag{4}$$

This process is mathematical described through Eqs. 3 and 4 where $\widehat{X} = Y * H^{-1}$ describes the noisy estimate of the received signal[5]. From a practical point of view this means that the transmitted signal (x_1) needs to be received in a different way on every receiving antenna ($y_{1,2}$) to creat a non-singular channel matrix. This so called well conditioned matrix provides the possibility to distinguish between different streams from the MIMO transmission[6]. In an typical indoor environment this de-correlation of the signals mainly arise from rays bouncing from walls and obstacles as well as short distance between the antennas leading to randomly distributed coefficients [10].

To exploit the possibility of MIMO, different signal processing techniques are included in the latest WiFi standard [5] namely Maximal-Ratio Combining (MRC), Space-Time Bloc Coding (STBC) and Spatial Multiplexing where MRC and STBC offer a gain in diversity and only spatial multiplexing has the ability of increasing the maximum capacity of the channel, in theory, linear by the number of antennas located at transmitter and receiver. Spatial Multiplexing with two antennas leads to additional MCS numbered from 8 to 15 with modulations and codings accordingly to the SISO equivalent 0–7.

Long Distances. Following the theoretical considerations regarding MIMO, different options to exploit this technique for long distance WiFi links arise where the main challenge is the de-correlation of the streams to reach a throughput increase by spatial multiplexing. The first option is spatial antenna diversity in combination with high gain directional antennas. The disadvantage of this option is the large spacing needed between the two antennas which is relative to the

[5] We use capital letters to describe the SISO and MIMO case.

[6] We can describe Eqs. 2 and 4 as the solution to a system of linear equations.

distance between the receiver and the transmitter. In [7] a model predicting the spacing needed and in [6] practical examples are given but both conclude, that such a deployment is not practical also because of the need for long coaxial cable. The second option is the usage of two antennas where one points to a large obstacle to force a multi path propagation due to reflexions. The typical WiBACK use-case bar this option on the one hand due to the rural environment and on the other hand because of complex process of antenna pointing not suitable for untrained persons. The third option is the usage of a single antenna with the ability of sending two streams with different polarizations called *cross-polarized antennas*. Depending on the quality and kind of antenna, there is an attenuation *between* the two signals of approximately 20–30 dB. This attenuation should lead to sufficient de-correlation of the signals in a long-distance environment to enable MIMO operation to increase the maximum throughput. This option has no known practical disadvantage and only a minor affect on the costs of our network equipment (CAPEX)[7].

3 Measurements

To evaluate and compare the behavior of .11n techniques on long distances different test links have been set up and utilized. A short link in a laboratory environment using stubby antennas serves as reference to evaluate the long distance influence. Two different long distance links have been installed, both originating at the Fraunhofer Campus in Birlinghoven, Germany. The first link terminates with non-perfect[8] conditions and a distance of 5 km at tree nursery while the second ends with perfect propagation conditions 10.3 km away on a radio tower. All three links with exception of the radio tower[9] use the same hardware, a tailor-made embedded computer equipped with dual Intel Atom N2800 CPUs and three Ubiquity SR71 wireless cards based on the Atheros AR9280 chipset. Two different kinds of MIMO antennas were used - a Ubiquity Rocket Dish 5G30 offering enough gain for high modulations over 10.3 km and a Mars MA-WA56-DP25NB at both sides of the 5 km link. The operating System is Debian Squeeze using a modified kernel which is optimized for long distance links in terms of MAC layer timings, contention window sizes and transmission buffer to ensure that enough packets are available for A-MPDU aggregation. As wireless driver serves ath9k and the rate control algorithm is PID while most of the time a fixed rate is chosen to prevent instable performance as shown in [13]. Some test beforehand proofs that with two notable exception every 802.11n-enhancement is already implemented in the ath9k driver - short guard interval and A-MSDU aggregation are not available in ad hoc mode. All measurements were done using a tool called *80211Analyzer* developed at Fraunhofer FOKUS at the receiver and the *mgen* traffic generator at the transmitter. The *80211Analyzer* receives WiFi frames via the monitor device which is working parallel to the standard interface

[7] The price of the cross-polarized antenna is marginally higher.

[8] LOS with obstacles looming in the Fresnel Zone.

[9] Slower CPU: AMD Geode LX 800.

Table 1. Fixed parameters for all measurements

Parameter	Value (default)
Distance (ACK-Timeout and Slot)	5 km/10 km (0.3 km)
Chance to retry a packet	1(7)
Transport layer protocol	UDP
Payload	1450 Bytes
Packets per second	=Physical-rate/Payload

offering the ability to evaluate all lower packet headers as well as - after reordering - any possible retransmissions and losses. To ensure comparability Table 1 shows a fixed set of parameters used for all following measurements.

3.1 Results

Utilizing the three introduced test scenarios this section describes the performed experiments and their results. By stepwise enabling the .11n features introduced in Sect. 2.1 we are in the situation of evaluating their applicability for long distance links separately. Figure 2 shows the result for enabling the OFDM-enhancements as well as A-MPDU aggregation with a maximum size of 2^{16} byte. By stepwise increasing the Modulation and Coding Scheme (MCS) from 0–7 every minute the physical data rate increases to 65 Mbps. The MAC layer

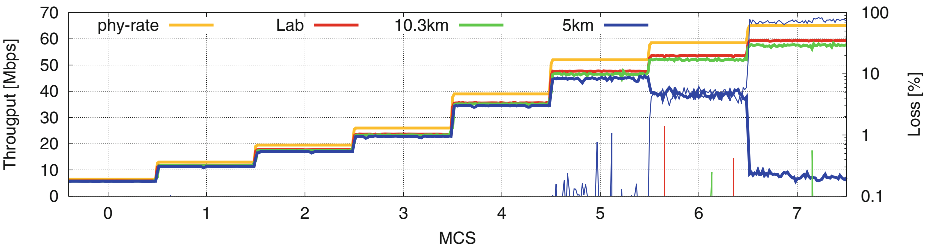

Fig. 2. OFDM-enhancements and A-MPDU

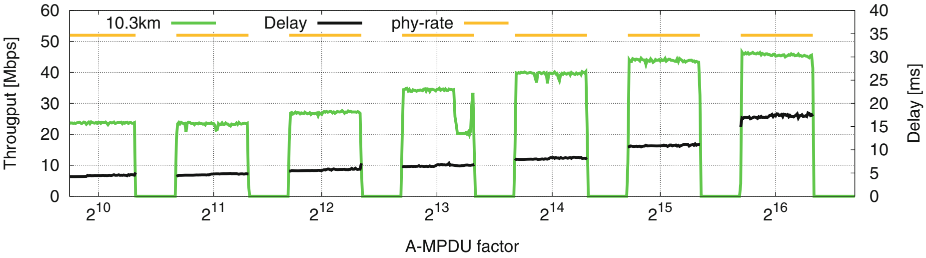

Fig. 3. Influence of the A-MPDU factor (fixed MCS 5)

aggregation successfully closes the gap between physical and real throughput induced in the .11a standard [14] by back-offs and inter-frame spaces so that the throughput for the laboratory and 10.3 km link raises simultaneously to 60 Mbps. A weak RSSI trough bad propagation conditions[10] causes that MCS 5 is the best rate for the 5 km link but the behavior for lower or equal to MCS 5 is identical to the other scenarios. To evaluate the inevitably increasing delay induced by aggregation we applied all available A-MPDU factors to the 10 km link as shown in Fig. 3. The first two A-MPDU factors have no difference in throughput and latency due to a large payload in combination with a MTU of 1470 byte. After that, the throughput increases with every doubling step of the A-MPDU factor. The increase is not linear, it is steep at the beginning and flattens at the end because of the fixed time for back-offs, IFS and block acknowledgments. As expected the latency rises with increasing A-MPDU factor which occurs due to the longer buffering of the packets before transmitting them in an aggregated way. While the relative throughput increase between the two highest A-MPDU factors is low, the increase in the latency is with 6 ms high in comparison, but also approximately computable[11]. Figure 4 pictures the applicability of cross polarized antennas to use .11n with spatial multiplexing. As described in Sect. 2.1 MIMO is a physical layer enhancement therefore loss is included in the plot instead of delay. It can be observed that the throughput

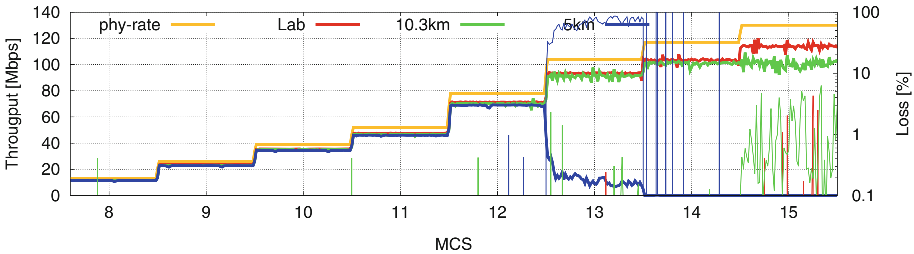

Fig. 4. Multiple input multiple output (20 MHz)

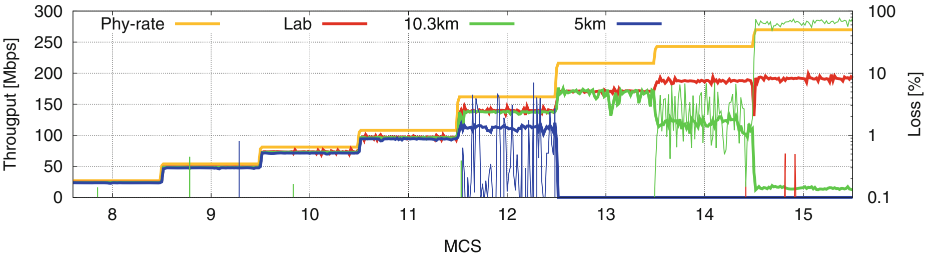

Fig. 5. 802.11n on long distance links

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[10] This applies to all forthcoming measurements as well.

[11] $\frac{2^{15} byte}{40 Mbps} = 6.5\, ms.$

increased nearly by factor two using the aerials in the laboratory *as well as* the cross polarized antennas on the long distance links. This indicates that the cross polarized antennas are suitable for long distance .11n MIMO links. The attenuation between the two streams on different polarizations is sufficient to form a nearly perfect channel matrix, which is an unexpected result. By increasing the channel width to 40 MHz our last measurement provides a complete view using all available 802.11n enhancements at the same time. Figure 5 pictures that the throughput in the laboratory environment increases to nearly 200 Mbps. As mentioned, the hardware at the radio tower is older with less CPU power than the other systems. With the usage of MCS 14 the CPU was saturated and the *mgen* process failed creating the amount of packets needed for this data rate. Nevertheless, the throughput rises up to 170 Mbps over 10km using 802.11n and by evaluating the lower modulation there are no reasons to assume that 200 Mbps are not possible.

4 Conclusion

By exploiting the main features of the IEEE802.11n standard, the maximum actual throughput for a 10 km link inside our WiBACK network increases from 30 Mbps to 170 Mbps measured in a real scenario. Hence, our results indicate that, for our investigated use cases, the IEEE802.11n physical enhancements are also applicable to long-distance links. With such data rates we are able to provide a cost and energy efficient alternative to existing technologies, such as fixed microwave links, in wireless Back-Hauling. The main difference between the laboratory environment and the two real point-to-point links is the increased acknowledgement timeout, which results in a slightly lower throughput. Especially the usage of a single cross polarized antenna provides a very cost-effective solution for increasing the throughput by nearly 100 % without any changes to other QoS parameters such as latency. Doubling the bandwidth to 40 MHz would have the same effect, but is often discouraged due to possible interferences with other links within the scarce frequency spectrum. Additional key features are the newly introduced MAC layer using packet aggregation and selective block ACKs. Considering the latency, this feature has the disadvantage of increasing the airtime of an aggregated frame, which may cause medium access latencies for concurrent traffic. However, the queuing time is predictable and packet aggregation is controllable in several ways by setting the A-MPDU factor and by enabling this feature just for certain traffic classes.

4.1 Future Work

Optimizing parameters such as back-off timings, AIFS for traffic class separation as well as various queue lengths is the next important step to further increase the Quality of Service and thereby the user experience in our WiBACK network. This optimization should be based on a traffic mix including different packet sizes, acknowledgments and face challenges occurring with protocols like TCP. We plan to apply the findings of this paper to sub-GHz WiFi (i.e. TVWS, 802.11ah) to increase the efficiency of this high potential frequency ranges.

Analytical Model. To perform this optimization we are currently evaluating, exploiting and extending different analytical models describing the IEEE802.11 MAC layer such as the one by Bianchi [15]. Describing our point-to-point links with an accurate model will provide us besides the optimization with the opportunity of a centralized capacity estimation of our network.

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