Multiple Input, Multiple Output Technology Accelerates Wired Home Networks

The MIMO enhancement to G.hn PLC adds another layer of robustness to its already strong technology foundation while nearly doubling G.hn’s industry-leading throughput.

Version 1.0 – June 2012
Note
THIS DOCUMENT IS PROVIDED "AS IS" WITH NO WARRANTIES WHATSOEVER, EXPRESS, IMPLIED, OR STATUTORY, INCLUDING WITHOUT LIMITATION, ANY WARRANTIES OF MERCHANTABILITY, NON-INFRINGEMENT, FITNESS FOR A PARTICULAR PURPOSE, OR ANY WARRANTY OTHERWISE ARISING OUT OF ANY PROPOSAL, SPECIFICATION, OR SAMPLE.

HomeGrid Forum disclaims all liability, including liability for infringement, of any proprietary or intellectual property rights, relating to use of information in this document. No license, express or implied, by estoppel or otherwise, to any proprietary or intellectual property rights is granted herein.

HomeGrid™, HomeGrid Forum™ and the HomeGrid Forum design are trademarks and/or service marks of HomeGrid Forum. All other names and logos are trademarks and/or service marks of their respective owners. Copyright © 2012 by HomeGrid Forum. Specifications and content subject to change without notice.

Author:
John Egan
Marvell Semiconductor, Inc

With contributions from:
AT&T, BT, Lantiq, Sigma Designs, and Metanoia
1 Overview
This paper introduces the Multiple Input, Multiple Output (MIMO) enhancement to G.hn’s Powerline Communications (PLC) mode, as defined in Recommendation ITU-T G.9963, the first PLC MIMO standard.

Since publication of the initial G.hn standards in 2010, the technology has attracted great interest from a growing number of companies. However, there have been a number of subsequent proposals to extend G.hn to make it even better. One such proposal was to enhance G.hn’s PLC mode with MIMO. The ITU-T standards committee began work on this in 2010, culminating in the G.9963 standard at the end of 2011.

G.hn PLC with MIMO brings several improvements over legacy PLC technologies, which are Single Input, Single Output (SISO):

- **Extended coverage** means even more places in the home can benefit from G.hn’s high Quality of Service (QoS) and Quality of Experience (QoE)
- **Improved signal** crossover between electrical phases also increases coverage and performance, which translates to increased throughput and better HD TV support
- Dramatically **increased throughput** from the spatial multiplexing of signals over two logical channels significantly augments capacity. MIMO for PLC boosts performance by at least a factor of 1.7 and so extends G.hn’s advantage over legacy technologies to a factor of more than 6 (1.7 times the previous 4-fold advantage).
- **Mitigation of attenuation** caused by power strips, surge protected outlets, and the numerous powerline branch circuits that exist in the home. This means performance is far less dependent on which power outlets the customer uses, resulting in consistent, high quality video streaming, and fewer support calls.
- **Improved performance** in mixed SISO and MIMO deployments through receiver diversity (SIMO mode) means backward compatibility with and improved performance for SISO G.hn networks
- G.hn’s **Neighboring Networks** technology with MIMO translates to improved service even in high density MDU deployments

G.hn’s PLC mode with MIMO takes a technology that already outperformed its rivals and makes it by far the most robust and powerful PLC home network choice available today. With a theoretical PHY data rate approaching 1.9 Gbps, approximately eight times the theoretical rate possible with today’s legacy SISO PLC technologies, and an error rate comparable with that achieved over coax cable, G.hn PLC with MIMO takes home networks to a new level. This ensures that the delivery of high data rate broadband services to the consumer are not bottlenecked by a slow home network or subjected to low quality of service. With the addition of MIMO, G.hn PLC mode is able to increase its reach and throughput, while becoming more resilient to noise and bit errors.

While speed claims get the headlines, it is quality of service and user experience that really matter. G.hn in PLC mode delivers on its promise of high quality of service and fine customer experience. Adding MIMO to G.hn increases network coverage, as well as boosts speeds, making the G.hn PLC MIMO network a future-proof investment, as demand grows for increasingly complex content and higher rate throughput.
2 PLC Background

There are two classes of PLC standardized by the ITU-T: low frequency G.hnem (G.9955 and G.9956), and the high frequency G.hn [1].

To provide data communications over power lines, PLC must overcome many obstacles. Power distribution cables, while efficient for electricity transport, are far from ideal for data transport because they lack balanced lines and signal protection. In addition to the wiring itself not being “data com friendly”, electrical wiring connections, meters, and breakers substantially attenuate PLC signals. PLC signal strength also decreases when branching off from the breaker panel and crossing between phases [1]. PLC signals also reflect off impedance mismatches, suffer delay spread, and are subject to the ingress of electro-magnetic interference.

Compounding these obstacles, various appliances and electrical devices in the home generate noise on the power wires. Because of all these factors, the noise and attenuation on the wires can, at any time, significantly deteriorate the PLC signals. However, the prevalence of powerlines and the near ubiquity of power sockets throughout the home make the use of the PLC highly desirable for in-home networking, as long as these obstacles can be overcome.

Legacy PLC systems are only able to overcome a subset of these obstacles. They use Single Input, Single Output (SISO) technology over the live and neutral lines, with transmission being on the live wire. Unfortunately, this is the wire that goes through surge suppressors, circuit breakers etc., and so PLC signals can be significantly deteriorated, or even blocked. For example, legacy PLC modems when plugged into surge protected outlet strips, provide mediocre service at best. Therefore, legacy PLC can be rather unreliable. Although marketed as a “200 Mbps” technology, legacy PLC systems typically achieve a worst-case rate of only 30 Mbps between 95% of the sockets in a home. To achieve 98% coverage reduces this rate to 10 Mbps [1].

![Figure 1: PLC SISO communications, where only the power and neutral wires are used](image)

Based on advances in modern digital signal processing and error mitigation techniques, OFDM-based G.hn provides dynamic mesh networking, selective retransmission of only the errored segments of packets, advanced LDPC Forward Error Correction, and adaptive bit loading per carrier (tone). With these techniques, and even without MIMO, G.hn is able to overcome some service impairments and deliver a clean, high-speed PLC data link that can achieve up to 950 Mbps[2]. The same theoretical calculation for legacy PLC results in the 200 Mbps figure for that technology.

G.hn also suffers, albeit to a lesser extent, when its signals encounter obstacles such as surge suppressors. G.hn with MIMO however virtually eliminates the impact of such devices by its use of multiple wires for transmissions.

[1] Use of the term ‘PLC’ throughout the paper refers to either ‘high frequency PLC’ or PLC as a generic term, based on context.

[2] This calculated value is under optimal theoretical conditions for G.hn PLC mode operating in the 2-100 MHz range; see “Appendices Calculating G.hn PLC data rate numbers” for example rates versus conditions.
3 PLC and MIMO

MIMO refers to a technique that utilizes more than one transmit path and more than one receive path; there are multiple inputs to the line from the node’s transmitters and multiple outputs to its receivers.

Wireless MIMO uses multiple transmit and receive antennas (and associated electronics) to provide different data paths, even though each path uses the same frequency. Wireless MIMO achieves better transmission and reception in crowded radio frequencies. Typically, this is when a wireless device is moving, and under heavy noise conditions. Moreover, when conditions are favorable, wireless MIMO transceivers can establish links at greater distances than SISO wireless devices. The use of beam forming with MIMO, which is based on a continuous flow of channel state data sent by receiver to transmitter, enables an “always-maximized” channel efficiency—and therefore increased throughput and reduced error rate. A G.hn receiver can also pass channel state information to the transmitter, and this functionality is included as part of G.hn PLC MIMO.

The use of multiple transmitters and/or receivers for PLC requires more than one electrical path between two communicating devices, with each path requiring at least two wires. In most homes around the globe, 3-prong electrical sockets are used, requiring three wires to the socket. The wires’ functional designations are ‘power’[^3], ‘neutral,’ and ‘ground’[^4]. G.hn nodes in PLC mode with MIMO are able to send as well as receive PLC signals using all three wires as two logical circuits.

![Figure 2: PLC over 3-wire, 120v service](image)

In some regions, such as Japan and Korea, and in some older homes elsewhere, only 2-wire sockets are used. Under these conditions, PLC MIMO does not bring additional benefit, nor does Single Input, Multiple Output (SIMO). In these places, G.hn’s SISO mode works well.

PLC with MIMO presents interesting phenomena due to the nature of PLC signal propagation over power lines. A PLC signal on one power line will propagate across to nearby lines, be they other power cables, or wires in the same cable. If the PLC signal is transmitted only over the power wire (such as with PLC SISO) it will propagate to the other wires in the same cable. If it is transiting a three wire cable, a SISO PLC transmit signal will propagate to the neutral and earth ground wires. This presents two scenarios.

[^3]: Also called ‘live’, ‘phase’ or ‘hot’
[^4]: Also called ‘protective earth’ or ‘earth ground’
The first is SISO transmit signals in a three-wire environment. As can be seen in the following Figure, a two-wire connection at a transmitter sends a data stream over the mains to a three-wire connection at a receiving node. This PLC signal propagates to the other wires of the three-wire bundle, in effect creating a second path for the data. This would be true in the case of a SISO transmitter, even if it was connected to a two-wire cable. If the receiving node has two receivers connected to a three-wire socket, and the ability to compare them, then based on this comparison, it would have a higher probability of detecting and decoding the original signal contents correctly. This improves the probability of error-free signal reception, which can result in higher data rates as well as reduced need for retransmissions, etc.

![Figure 3: Propagation of PLC signal to other wires](image)

The second scenario is related to the complexity of MIMO transceivers and how the receiver must be able to decode arriving signals, which are on the same frequencies but have propagated to another wire. This inherent crosstalk is a substantial hurdle that PLC with MIMO must overcome. The G.9963 standard defines how to cyclically shift the second signal so that it is able to be detected and decoded versus the other path’s crosstalk and vice versa, thus overcoming inter-path crosstalk.

<table>
<thead>
<tr>
<th>TX port #1</th>
<th>Header 1, 2 or 4 symbols</th>
<th>ACE symbol(s)</th>
<th>payload #1</th>
</tr>
</thead>
<tbody>
<tr>
<td>TX port #2</td>
<td>Header (with CS)</td>
<td>ACE symbol(s) (with CS)</td>
<td>payload #2 (with CS)</td>
</tr>
</tbody>
</table>

**Note 1:** Preamble and header transmitted on TX port #2 are cyclic-shifted versions of their counterparts transmitted on TX port 1  
**Note 2:** The Additional Channel Estimation (ACE) symbol transmitted on TX port #2 is the cyclic-shifted and inverted version of the ACE symbol transmitted on TX port #1  
**Note 3:** a cyclic shift is applied to the payload symbols transmitted on TX port #2

![Figure 4: Use of cyclic shift in G.hn MIMO transmissions](image)

4 G.hn PLC mode with MIMO

G.hn, with its innovative networking technology, is pioneering important changes in home network equipment. Even the initial G.hn standards allowed more than one receiver. Therefore, one should not regard “regular” G.hn PLC nodes as being limited to SISO, as this may not be true for a given implementation. Non-MIMO G.hn nodes should therefore be generically termed ‘SISO’.

In a G.hn PLC network, when the recipient node attached to a 3-wire socket does have two receivers, they can both listen to the three-wire service. This is similar to a well-documented wireless technique called receiver diversity. All G.hn SIMO and MIMO nodes support receiver diversity and thereby achieve higher data rates and a reduction in error rate when communicating over 3-wire links, even if there is a non-MIMO transmitter node transmitting, or the far end node is operating over a 2-wire socket (see table below).

[5] The term ‘SISO’ used here to denote that a G.hn node might have more than one receive path while it has one transmit path. The node’s transceiver would have to support more than one receive path (be a SIMO node) and the node would have to be attached to a 3-wire socket to gain efficiencies based on its SIMO capabilities.
G.hn nodes with MIMO achieve an increase in efficiency over the same PLC frequencies by using space (path) diversity at both the transmitter and receiver. As a result: (a) G.hn’s PLC service has increased noise immunity; (b) signals at the same data rate may reach further, thus reducing the cost of overall network deployment; and (c) higher data rates between G.hn nodes are possible. While MIMO is the typical operational mode for a G.hn PLC MIMO node, there are cases where the far end node, in-home electrical wiring, or the socket types used, may preclude MIMO operation. The following table shows the resulting communication mode (SISO, SxO, SIMO, or MIMO) between a transmitter and receiver, given the transceiver and socket types. If a socket type is 3-wire, it is assumed for the purposes of the Table that three wires are attached to the socket.

Table 1: Communication modes possible for different G.hn node types on 2 and 3-wire sockets

<table>
<thead>
<tr>
<th>Transmitting node</th>
<th>To 2-wire sockets</th>
<th>To 3-wire sockets</th>
</tr>
</thead>
<tbody>
<tr>
<td>From 2-wire sockets</td>
<td>G.hn SxO</td>
<td>SISO</td>
</tr>
<tr>
<td>G.hn MIMO</td>
<td>SISO</td>
<td>SISO</td>
</tr>
<tr>
<td>From 3-wire sockets</td>
<td>G.hn SxO</td>
<td>SISO</td>
</tr>
<tr>
<td>G.hn MIMO</td>
<td>SISO</td>
<td>SISO</td>
</tr>
</tbody>
</table>

Note: The use case of 3-wire sockets and cabling is the predominant one globally, enabling full MIMO service.

The table highlights another benefit of G.hn PLC with MIMO. When MIMO G.hn nodes are added to an existing non-MIMO G.hn network, their ability to improve reception over three-wire sockets, even from non-MIMO nodes, will improve overall network efficiency.

G.hn also uses a more robust and efficient signaling method and MAC layer than legacy PLC technologies. Therefore, G.hn PLC using only a single transmitter and single receiver (SISO mode) performs better than its rivals, achieving a maximum data rate nearly three times its fastest standardized competition (IEEE 1901 FFT with the optional 50 MHz band[6]) and more than four times HomePlug AV, or any 30 MHz IEEE 1901 PHY. In this scenario, G.hn in SISO mode has only been compared with these legacy SISO PLC technologies. G.hn PLC with MIMO can achieve a further near 2-fold increase in PHY data rate, making it up to five times faster than the fastest standardized PLC competitor, and more than nine times faster than HomePlug AV. Note that all these comparisons are based on comparable PHY rate calculations and theoretical limits.

[6] IEEE 1901 defines two completely non-interoperable PLC MAC/PHY technologies, ‘1901 FFT’ and ‘1901 Wavelet’. Both define mandatory 2-30 MHz operation while 1901 FFT has an optional 30-50 MHz band. To keep confusion low, the term ‘1901 FFT with optional 50 MHz band’ references 1901 FFT performance over the 2-50 MHz range.
There is an ever increasing "need for speed" to satisfy consumers’ desire for the fastest, most reliable network in their homes delivering high bit rate communications services and content anywhere, at any time. Theoretically, SixO PLC mode G.hn can achieve more than 950 Mbps wire speed while G.hn PLC mode with MIMO is able to double this to more than 1.9 Gbps\(^7\). Under more real-world conditions, over 400 Mbps application layer throughput is possible with G.hn PLC with MIMO increasing this to 675 Mbps. Therefore G.hn with MIMO comprehensively satisfies both today’s need for speed in the home network, and will continue to do so for the foreseeable future.

5 PLC and MIMO in Multi-Dwelling Buildings – A Unique G.hn Strength

In a multi-dwelling unit (MDU) building, inter-network PLC interference (between the networks of different dwellings) is frequently encountered and can sometimes be a significant problem. It is caused by PLC signals coupling between the power wires that serve the individual dwellings, resulting in interference. MIMO could actually make this problem worse, as it may enable stronger PLC signals from one living unit to reach another unit. The following Figure shows the wire paths that can be taken between two apartments.

With legacy PLC, the signals are only transmitted over the power lead, where they suffer signal attenuation due to circuit breakers and meters. This attenuation is not enough to eliminate inter-unit network interference however, and so neighboring legacy PLC networks may interfere with one another to the point where there is a substantial deterioration in service.

Legacy PLC technologies require either a physical and/or transmission-based solution to this problem. The service provider could install blocking filters, or the networks could use a time division methodology to avoid the neighboring network interference. The filters are relatively expensive and may not resolve the matter fully and filters are particularly ineffective for a MIMO application. Time division multiplexing between networks results in dramatically reduced throughput for each network.

However, G.hn has “Neighboring Networks” (NN) technology. This allows for multi-network coordination, signal differentiation, and spatial reuse, virtually eliminating the problem of inter-unit interference.

---

\(^7\)The theoretical nature of PLC numbers comes into play here as the ability of a MIMO link to deliver more than 2 x the SISO rate is well documented in papers, yet real world numbers vary widely depending on several factors such as noise conditions, length of the cable link between nodes, and the topology of the power cabling. A conservative estimate is 1.7 times the SISO rate, this is the rate used throughout the text.
network interference. G.hn PLC mode with NN ensures maximum throughput for each network with little, if any impact, from neighboring G.hn PLC networks.

![Figure 7: PLC signals crossing between MDU apartments](image)

In a MIMO scenario, PLC signals traverse the Neutral and Ground wires, and experience less attenuation, arriving at other apartments with relatively high signal strength, thus increasing the likelihood of substantial interference between PLC networks. However, G.hn PLC mode (with or without MIMO) with NN technology virtually eliminates the cross-network interference between G.hn MDU PLC networks. The details of NN inter-network noise mitigation are discussed in a separate paper from HomeGrid Forum due for publication summer of 2012.

Therefore, MDUs with neighboring networks are a problem for other PLC technologies, and the inter-network interference increases if and when they add MIMO, thereby decreasing, rather than improving, the service quality. However, inter unit interference is not a problem for G.hn networks with NN technology, and so the addition of MIMO to G.hn will improve its performance in MDUs, as well as in individual houses.

6 Summary

PLC has come of age with the arrival of G.hn. G.hn PLC takes a technology, which was only capable of “best effort” data transport, and places it on par with coax and the other wireline media that have high throughput and Quality of Service capabilities (e.g. Cat 5 UTP).

The G.9963 MIMO enhancement to G.hn enables G.hn PLC nodes to outperform any other PLC technology while remaining fully interoperable with existing G.hn non-MIMO PLC nodes.

G.hn’s MIMO enhancement uses Spatial Multiplexing and Precoding to maximize performance in three ways: under high noise conditions, over extended distances, and by increasing the data rate by nearly a factor of 2. Moreover, G.hn’s Neighboring Networks technology avoids the interference that afflicts other PLC technologies in MDUs, with or without MIMO.
The bottom line is that improvements in G.hn with MIMO take a technology that already outperformed its contemporaries, and make it by far the fastest and most robust wired home networking choice available that avoids installing new wires.

There is the prospect of further enhancements as the HomeGrid Forum and ITU-T continuously work on improving how data can be moved not just fast, but completely error-free over the home network, enabling “connectivity anywhere” with the delivery of multiple streams of high data rate content, such as HD TV, anywhere in the home.

REFERENCES
Appendix

I. Calculating G.hn PLC data rate numbers

The following table lists variables and frequency ranges, and provides the calculated possible G.hn PLC mode PHY (on the wire) and MAC (application throughput) data rates.

Calculating the data rates for PLC is not an exact science as each pair of nodes in any PLC network experiences its own unique set of obstacles to communication, and such obstacles may be time varying in nature and intensity. Further, PLC transmission is subject to factors related to frequencies (e.g., low frequencies are more subject to noise, while higher frequencies experience high attenuation). Therefore, the following values are presented only for comparison. Included here are the theoretical maxima for G.hn PLC mode with and without MIMO, with examples of more real world numbers under various conditions. These assume a “clean” connection, with no retransmissions required.

Column Designations:
- A) 100 MHz Theoretical Maximum for G.hn MIMO, no notches
- B) 100 MHz G.hn MIMO with International Ham notches but without the FM notch
- C) 100 MHz G.hn MIMO with the International Ham notches and the FM notch
- D) 100 MHz Theoretical Maximum of G.hn SISO, no notches
- E) 100 MHz G.hn SISO with the International Ham notches and the FM notch
- F) 50 MHz G.hn SISO & MIMO at its theoretical maximum, no notches
- G) 50 MHz G.hn SISO & MIMO with International Ham notches

<table>
<thead>
<tr>
<th>Example type</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency Range (MHz)</td>
<td>2-100</td>
<td>2-100</td>
<td>2-100</td>
<td>2-100</td>
<td>2-100</td>
<td>2-50</td>
<td>2-50</td>
</tr>
<tr>
<td>Avg. bits per carrier[^9]</td>
<td>12</td>
<td>7.79</td>
<td>8.3</td>
<td>12</td>
<td>8.3</td>
<td>12</td>
<td>9.75</td>
</tr>
<tr>
<td>International Ham bands notched</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Notched at 80 MHz for FM</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Highest used frequency</td>
<td>100</td>
<td>100</td>
<td>80</td>
<td>100</td>
<td>80</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Effective spectrum used (MHz)</td>
<td>98</td>
<td>90.45</td>
<td>70.45</td>
<td>98</td>
<td>70.45</td>
<td>48</td>
<td>44.45</td>
</tr>
<tr>
<td>No. of payload symbols</td>
<td>128</td>
<td>128</td>
<td>128</td>
<td>128</td>
<td>128</td>
<td>128</td>
<td>128</td>
</tr>
<tr>
<td>FEC rate[^10]</td>
<td>20/21</td>
<td>5/6</td>
<td>5/6</td>
<td>20/21</td>
<td>5/6</td>
<td>20/21</td>
<td>5/6</td>
</tr>
<tr>
<td>Non-MIMO PHY rate (Mbps)</td>
<td>959.12</td>
<td>573.08</td>
<td>475.12</td>
<td>959.12</td>
<td>475.12</td>
<td>469.76</td>
<td>381.63</td>
</tr>
<tr>
<td>Non-MIMO MAC rate (Mbps)</td>
<td>913.44</td>
<td>477.57</td>
<td>395.93</td>
<td>913.44</td>
<td>395.93</td>
<td>447.39</td>
<td>318.02</td>
</tr>
<tr>
<td>MIMO factor[^11]</td>
<td>2.0</td>
<td>1.7</td>
<td>1.7</td>
<td>2.0</td>
<td>1.7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

[^8] Conditions calculated as the same over each path, although they will differ in the field. Moreover, the FEC rate is fixed per example to simplify the table. International Ham bands are notched in all examples but the theoretical maxima (columns A, D & F)

[^9] The values used for average bpc are: either 12 bpc in all frequency ranges to show the theoretical maximum or the following assignments: 11 bpc used for 2-30 MHz, 8 bpc for 30-50 MHz, and 6 for above 50 MHz

[^10] The FEC values used are either 20/21 to show the theoretical limit and 5/6 to show a much more conservative scenario
PHY rate with MIMO (Mbps)  
<table>
<thead>
<tr>
<th>Rate</th>
<th>1918.23</th>
<th>974.24</th>
<th>807.7</th>
<th>939.52</th>
<th>591.8</th>
</tr>
</thead>
</table>
MAC rate with MIMO (Mbps)  
| Rate         | 1826.89 | 811.87 | 673.08 | 894.78 | 493.17 |

Note: While G.hn defines transmissions up to 100 MHz over any wireline medium, the G.hn standard notches the PLC frequency bands above 80 MHz to avoid the FM radio spectrum. Operation above 80 MHz, while possible with G.hn PLC, is not recommended unless regulatory and FM interference issues are resolved. ([http://www.itu.int/ITU-R/index.asp?category=conferences&rlink=itu-plt-forum-11&lang=en](http://www.itu.int/ITU-R/index.asp?category=conferences&rlink=itu-plt-forum-11&lang=en)).

The reasoning behind placing the notch at 80 MHz instead of just below the actual lowest frequency of the FM bands (86 MHz) is due to the practicalities of system and silicon design to ensure there are no side lobes or cross frequency interference into the FM band. Serious consideration was given to this matter and a very realistic 80 MHz limit was agreed upon between radio and PLC experts. Those claiming their technology operates above this frequency are either creating FM interfering systems or making marketing claims that do not reflect the actual frequency their products operate up to when installed in the field.

[11] The MIMO multiplier of 1.7 is a reasonable factor while the factor of 2 is a theoretical number used to show a near maximum result. The MIMO factor is dependent on several aspects such as SNR, where the lower the SNR the lower the MIMO factor. The factor may range up to 2 times or more versus the non-MIMO rate