Design and Performance Analysis of Multiradio Multihop Network Using IEEE802.11n 2.4GHz Access and 5.8GHz Backhaul Radios

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Abstract. This paper presents the design and performance insights of a multiradio multihop network using IEEE802.11n radios. The widely adopted architecture that uses 2.4GHz access and 5.8GHz multihop backhaul links is considered. More specifically, this study looks into the feasibility of such design to provide backhauling between two base stations while providing WiFi access along the multihop routers. The analysis covers the performance of different designs or configurations such as distance between hops, multihop chain distance, choice of Modulation and Coding scheme (MCS), backhaul link rate, channel bandwidth, number of spatial streams required to support certain capacity per AP and connection rate per user. The findings show that by ignoring the number of hops required, at least 3 MIMO spatial streams and 16QAM3/4 are required to support the basic 2Mbps connection rate per user per AP along the multihop chain. This is on top of 120Mbps raw physical data rate required to provide backhaul connectivity between the base stations.

Keywords: WiFi, IEEE802.11n, Wireless Multihop, Wireless Mesh.

1 Introduction

The needs to provide broadband wireless access coverage rapidly and cost effectively continue to fuel innovations in the area of wireless mesh or multihop networking (WMN). Over the years WMN technologies particularly the WiFi mesh, have evolved from single radio systems to multiradio systems involving heterogeneous radio interfaces such as IEEE802.11a,b,g and n. The most commonly known industrial practice adopts the architecture which consists of IEEE802.11a radio as backhaul and IEEE802.11g for the access. This is largely motivated by the fact that IEEE802.11a has more non overlapping channels and much less congested spectrum band therefore giving a better performance. IEEE 802.11n standard [1], which introduces Physical data rates up to 600Mbit/s using MIMO technology and increased tolerance to interference looks promising to push up the capacity limitation of WMN.

Many household mesh vendors have already included the IEEE 802.11n radio into their solutions and products design. Ruckus claims to provide more efficient indoor enterprise wireless mesh without using the new 5GHz band due to the use of directional beam forming technique [2]. Meraki offers 3-radio 802.11n outdoor mesh

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product that costs $500 per radio [3]. Tropos later joined the 11n-Mesh club by releasing the x6320 routers which start at $2,995 [4]. Motorola soon after that announced the high-performance, reliable and secure 802.11n outdoor mesh wide area network (MWAN) solution [5]. More recently Strix Systems released its new solution which supports up to six (6) radios in various design options including 11n MIMO, 4.9GHz, as well as a choice between licensed or unlicensed frequencies [6].

On related research works, [7] modified the existing IEEE 802.11n MAC to support aggregation of both unicast and broadcast frames, and analyzed the throughput performance of their design over 2 and 3-hop chain topologies. [8] characterizes the effective throughput of IEEE802.11n-based multihop network and analyzed the upper bound throughput at MAC layer as a function of bit error rate, frame aggregation level and path length. [9] investigates the effectiveness of different MAC (Medium Access Control) and transmission rate adaptation schemes on wireless mesh networks such as IEEE 802.11, 802.11e, and 802.11n MAC, and three rate adaptation schemes, i.e., ARF (Automatic Rate Fallback), RBAR (Receiver-Based Auto Rate), and 802.11n rate adaptation. However the scope of the works above is only limited to single radio system. Furthermore [7] and [8] mainly focus on improving TCP transmission.

Although there is a wide range of 11n-based wireless mesh/multihop network products and solutions, the performance of such network is not well understood especially from the capacity and range (coverage) point of view. Clearer insights are needed on the relationships between number of hops, multihop distance, backhaul link rate, modulation and coding scheme (MCS), number of MIMO spatial stream, channel bandwidth, and effective capacity per access point which can later be translated into connection rate per user, etc.

This paper is organized as follows: section 2 presents the assumptions required for this high level analysis. Section 3 introduces methodology, equations and related models used. General parameters and results are discussed in section 4. Finally, conclusions and future work are drawn in section 5.

2 Assumptions

2.1 Potential Application Scenario

Multiradio multihop network with separate access and backhaul radios offer a variety of application scenarios. Figure 1shows a potential application scenario where while providing alternative backhaul link to two base stations, the network can also provide wireless access to end users along the multihop chain.

Logically the backhaul radio will be using directional antenna and the typical omni-directional antenna for the access. Different access radio types can also be considered depending on coverage, capacity as well as user requirement. Such feature is particularly attractive in places where wired backhaul is expensive or not available. Also while providing alternative backhaul and access, such design also offers the benefit of offloading for the macro cells as illustrated in Figure 2.

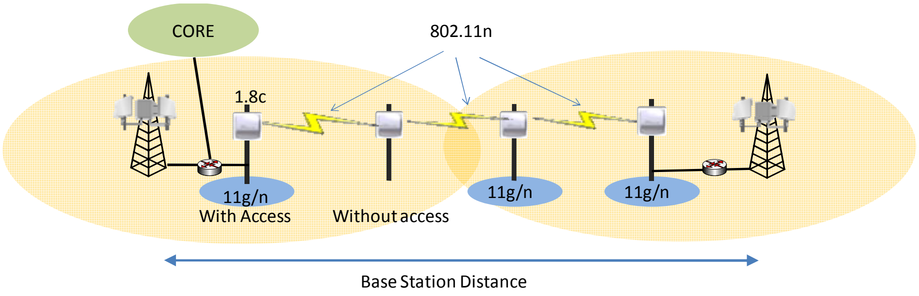

Fig. 1. Potenial scenario using multi-hop network between two macro base stations

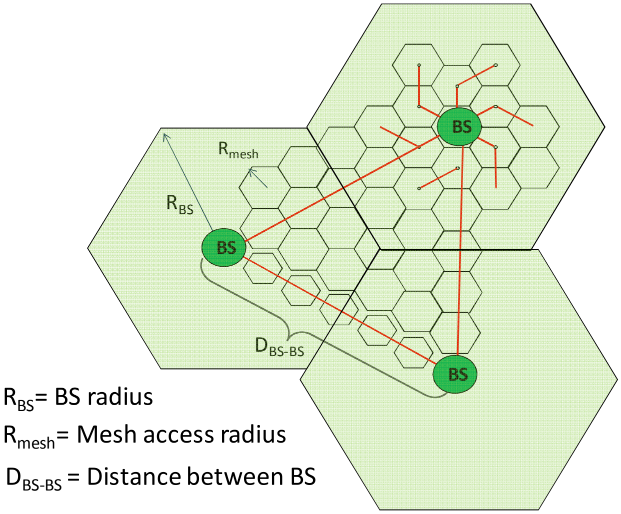

Fig. 2. Exempler topology based on scenario in Figure 1

2.2 Data Rate and Overbooking Factor

The target backhaul data rate for each Access Point (AP) is representative of the connection speed (or headline speed) typically sold by a network operator. The overbooking factor (OF) is the ratio of the potential maximum demand to the actual bandwidth consumed. A typical OF assumed for internet browsing is around 50:1 and for higher bandwidth applications such as video streaming or FTP, the OF is around 10 or 20:1 [10]. In other words, the lower the OF the higher the mean bandwidth or QoS demand for that service. This is subsequently translated to data rate per user which represents the maximum downlink rate that can be enjoyed by each end user.

2.3 Interference

Interference arising from co-channel, adjacent channel and foreign devices are assumed to be minimal and are represented as a margin increase. For the 5 GHz spectrum, this assumption is reasonable as there are 23 non-overlapping channels available (North America). Hence even with channel bonding there will be 11 non-overlapping 40MHz channels. For the access at 2.4GHz, since the access capacity is unlikely to exceed the backhaul, 3 non-overlapping 20MHz channels is sufficient to provide some degree of interference mitigation.

2.4 Fair Sharing of Bandwidth for AP

Within a cluster, bandwidth is fairly distributed across all APs so that nodes with more hops away from the gateway enjoy the same bandwidth as compared to those nodes nearer to it. This can be achieved by applying various well-known techniques described in existing literatures such as traffic admission control at the AP and fair bandwidth scheduling at the MRAR. It is also assumed that 100% traffic is flowing between users/APs and gateway hence base station [10] .

3 Model

This section describes the methodology, equations and related models used to develop our model.

Table 1. Notations

Notation	Description
PL	path loss in dB
$EIRP$	effective isotropic radiated power
G_{rx}	receiver antenna gain
M_{total}	total margin such as shadow, interference, fading, etc.
R_{sen}	receiver sensitivity
C_{phy}	ideal data rate at the PHY layer
$C_{eff}^{\downarrow}$	effective downlink data rate at IP layer
φ	link efficiency measured at the IP layer
$DLUL$	Downlink to uplink traffic ratio
$DR^{\downarrow}$	designed data rate at the downlink
$\overline{DR}^{\downarrow}$	statistical average data rate at the downlink
N_{SS}	number of spatial stream
R	coding rate
N_{SD}	number of complex data numbers per spatial stream per OFDM symbol
T_{SYM}	symbol duration
N_{hop}	Number of wireless hops

Typical receiver sensitivity values per modulation and coding scheme (MCS), channel bandwidth and corresponding physical data rate for different number of spatial streams are tabulated in TABLE 2.

Table 2. IEEE802.11n Receiver Sensitivity, MCS, Channel Bandwidth and PHY Data Rate

MCS	**Receiver Sensitivity**		**Physical Data Rate** where (N_{ss}= 1/2/3/4)	
	20MHz	**40MHz**	**20MHz**	**40MHz**
BPSK 1/2	-95.0	-91.0	7.2 Mbps x N_{ss}	15 Mbps x N_{ss}
QPSK 1/2	-93.0	-90.0	14.4 Mbps x N_{ss}	30 Mbps x N_{ss}
QPSK 3/4	-90.0	-87.0	21.7 Mbps x N_{ss}	45 Mbps x N_{ss}
16-QAM 1/2	-87.0	-84.0	28.9 Mbps x N_{ss}	60 Mbps x N_{ss}
16-QAM 3/4	-84.0	-82.0	43.3 Mbps x N_{ss}	90 Mbps x N_{ss}
64-QAM 2/3	-80.0	-78.0	57.8 Mbps x N_{ss}	120 Mbps x N_{ss}
64-QAM 3/4	-79.0	-76.0	65.5 Mbps x N_{ss}	135 Mbps x N_{ss}
64-QAM 5/6	-77.0	-74.0	72.2 Mbps x N_{ss}	150 Mbps x N_{ss}

The general link budget used is:

$$PL = EIRP - R_{sen} + G_{rx} - M_{total} \tag{1}$$

For each MCS, the physical data rate of IEEE802.11n can be derived using the following equations:

$$C_{phy} = \frac{N_{SD}}{T_{SYM}} * R * N_{SS} \tag{2}$$

Consequently the effective downlink data rate at IP layer,

$$C_{eff}^{\downarrow} = C_{phy} * \varphi * DLUL \tag{3}$$

From (3) and by assuming simultaneous transmissions with multiradio support, the effective capacity per AP or per hop can be defined as:

$$C_{eff,AP}^{\downarrow} = \frac{C_{eff}^{\downarrow}}{N_{hop}} \tag{4}$$

The required statistical average data rate (per direction) per Mesh AP $\overline{DR}$, is given by [10]:

$$\overline{DR}^{\downarrow} = \frac{DR^{\downarrow}}{OF} \tag{5}$$

In this study we only focus on the downlink direction as the uplink can be easily deduced from equation (3). From (3) ,(4) and (5) we can get the maximum possible number of users supported by a mesh AP at data rate DR, $N_{user,max}^{DR\downarrow}$with the condition that effective IP layer data rate per AP, $C_{eff,AP}^{\downarrow}$ must be larger than the designed data rate.

$$N_{\boldsymbol{user,max}}^{DR\downarrow} = \begin{cases} \left\lfloor \frac{C_{eff,AP}^{\downarrow}}{\overline{DR}^{\downarrow}} \right\rfloor, & C_{eff,AP}^{\downarrow} \geq DR^{\downarrow} \\ 0, & otherwise \end{cases} \tag{6}$$

4 General Parameters and Results

4.1 General Parameters

Both access and backhaul radios are using IEEE802.11n with access at 2.4GHz and backhaul at 5.8GHz respectively. The Effective Isotropic Radiation Power (EIRP) for 2.4GHz and 5.8GHz are set at 27dBm and 30dBm respectively, which are the maximum EIRP allowable for these frequency bands in Malaysia. The TDD ratio is set at 3:1 assuming that the APs are predominantly serving downlink intensive applications such as Internet browsing. Overbooking factor of 50:1 is assumed to represent typical residential usage scenario. The link layer efficiency is assumed to be around 50% of physical layer data rate. This means only 50% of the physical layer raw data rate will be translated to IP layer's throughput [11]. Although there are some differences between TCP and UDP traffics in terms of link layer efficiency, the value 50% is believed to be appropriate for general representation. The parameters and default values used for the subsequent experiments are summarized in 0.

Table 4. General parameters and values

	Units	WiFi
RF		
Frequency band (access/backhaul)	GHz	2.4/5.8
EIRP (access/backhaul)	dBm	27/30
G_{rx} (backhaul)	dBi	15
G_{rx} (user terminal)	dBi	0
φ		0.5
Propagation model	Modified Free Space Path Loss model (urban)	
Path Loss Coefficient	3.5 (access), 2.0 (backhaul assuming LOS)	
Interference	dB	3
System and User requirements		
DLUL		3:1
OF		50:1
$DR^{\downarrow}$	Mbps	2, 5
Distance between base stations		
Reserved end to end data rate between base stations	Mbps	120 (raw physical) for typical 4G base station

4.2 Results

A) Effective capacity per AP vs. MCS type vs. Number of spatial streams

In Figure 3 the relationship between effective capacity per AP, MCS used and number of spatial streams at 20 and 40MHz channel can be deduced. As expected, effective capacity increases with higher order MCSs. It is also shown that to achieve at least 2Mbps per AP, 2 spatial streams of 40MHz channel is required. For 20MHz, at least 4 streams are required using 64QAM3/4 and 64QAM5/6. One interesting finding here is that the best capacity per AP (17Mbps) is found to be provided by 64QAM2/3 rather than higher order schemes such as 64QAM3/4 or 64QAM5/6. However, the result does not reveal the difference between the number of hops along the 3km distance required by each configuration.

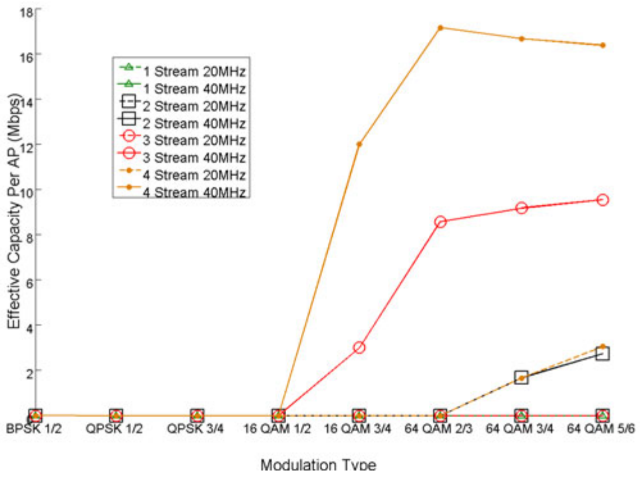

Fig. 3. Capacity per AP vs. type of MCS at backhaul vs. number of spatial streams at backhaul using 20MHz and 40 MHz channel. Multihop chain network distance is fixed at 3km with equidistance between hops and 120Mbps raw physical rate reserved for base stations.

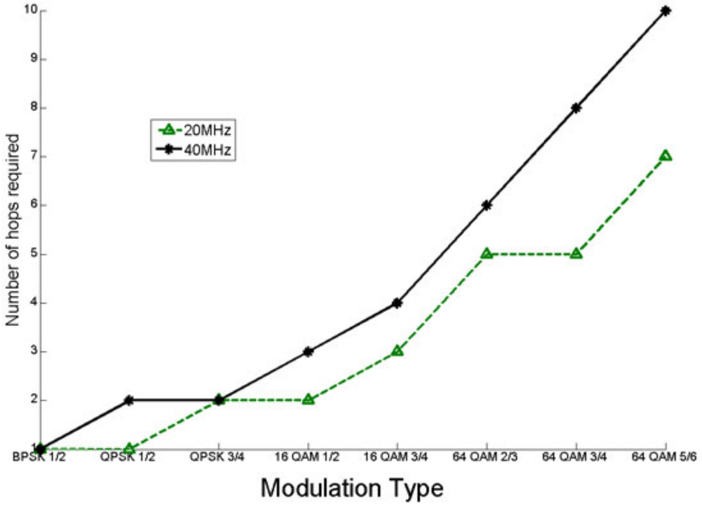

Fig. 4. Total number of hops required vs. MCS at backhaul with multihop chain network distance fixed at 3km and equidistance between hops

Figure 4 shows that the number of hops increases when higher order MCSs are used. This is expected as higher order MCS higher requires higher receiver sensitivity therefore lower distance between hops. It can also be deduced that highest order MCS such as 64QAM5/6 requires at least 10 hops using 40MHz channel while 20MHz only requires around 7 hops in order to cover a distance of 3km.

B) Data rate per user

Next, the design requirements for supporting two typical data rates currently offered to wireless broadband customers 1) 2 Mbps and 2) 5Mbps are investigated.

B.1) 2 Mbps connection rate per user

Figure 5 shows that 20MHz channel is unable to support 2Mbps connection rate per user even with overbooking factor of 50:1.

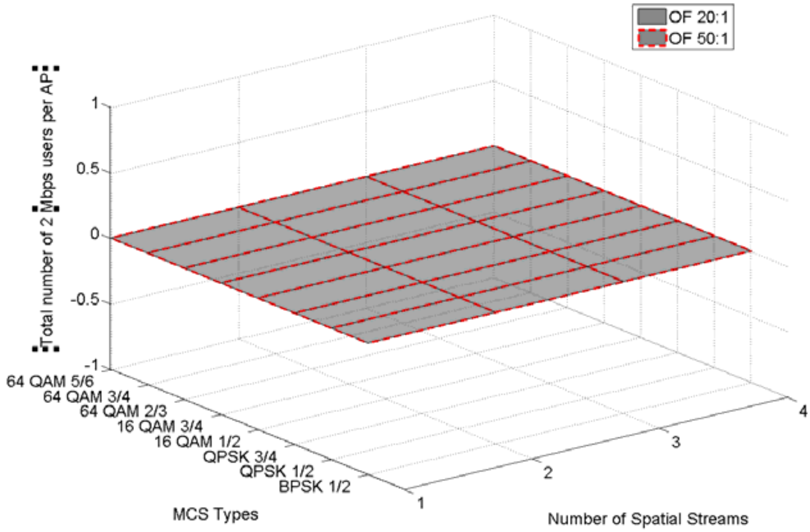

Fig. 5. Number of 2Mbps users supported per AP vs. type of MCS at vs. number of spatial streams over 20MHz Channel. Multihop chain network distance is fixed at 3km with equidistance between hops and 120Mbps raw physical rate reserved for base stations

As shown in Figure 6, using 40MHz channel over the same configuration, up to 200 simultaneous 2Mbps connections per AP with OF=50:1 can be supported using 4 spatial streams at 64QAM5/6. For more demanding applications which require OF of 20:1, only up to 80 users per AP can be supported. MCS with 16QAM1/2 and lower are unable to support any user with 2Mbps connection rate due to the limitation stated in equation 6. It can also be derived from the figure that at least 3 spatial streams are required to support 2Mbps connection rate per user.

As observed in Figure 7, using 40MHz channel over the same configuration, up to 50 simultaneous 5Mbps connections per AP with OF=50:1 can be supported using 4 spatial streams at 64QAM5/6. For more demanding applications requiring OF of 20:1, only up to 20 5Mbps users can be supported per AP. MCS with 16QAM3/4 and lower are unable to support any user with 5Mbps connection rate. It is also shown that at least 4 spatial streams are required to meet this requirement.

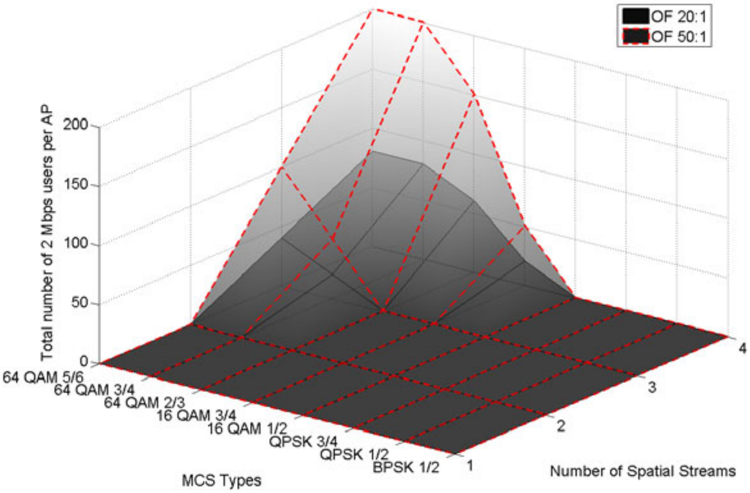

Fig. 6. Number of 2Mbps users supported per AP vs. type of MCS at vs. number of spatial streams over 20MHz Channel. Multihop chain network distance is fixed at 3km with equidistance between hops and 120Mbps raw physical rate reserved for base stations.

B.1) 5 Mbps connection rate per user

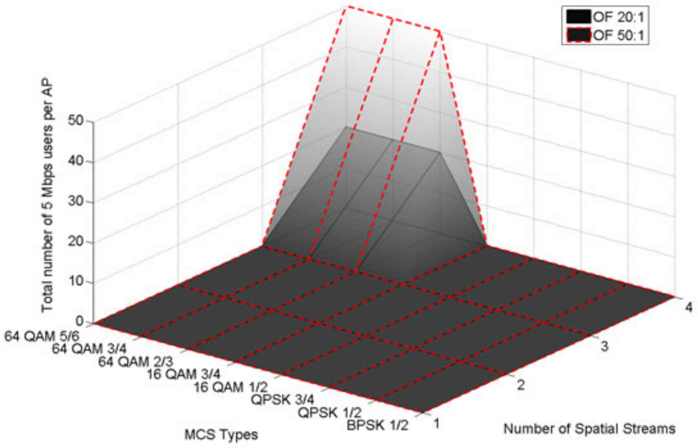

Fig. 7. Number of 5Mbps users supported per AP vs. type of MCS at vs. number of spatial streams over 40MHz Channel. Multihop chain network distance is fixed at 3km with equidistance between hops and 120Mbps raw physical rate reserved for base stations.

5 Conclusion and Future Work

In this paper, a high level design and analysis on the of multiradio multihop network using IEEE802.11n access radio at 2.4GHz and 5.8GHz for backhaul radio have been carried out. Various configurations such as MCS/distance between hops, backhaul link rate, multihop chain distance, channel bandwidth, number of spatial streams required to support certain capacity per AP and connection rate per user have been investigated. A general conclusion can be derived from this study is that by ignoring the number of hops required, at least 3 MIMO spatial streams and 16QAM3/4 are required to support the basic 2Mbps connection rate per user per AP along the multihop chain network. This is on top of 120Mbps raw physical data rate required to provide backhaul connectivity between base stations.

Future work shall take into consideration of the access coverage and degree offloading that can be provided by this design. There scenario will also be extended to include multihop tree or mesh topology.

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