On the Achievable Throughput of Multi-Band Multi-Antenna Wireless Mesh Networks

Bechir Hamdaoui
School of EECS, Oregon State University
hamdaoui@eecs.oregonstate.edu

Kang G. Shin
Dept. of EECS, Univ. of Michigan
kgshin@eecs.unich.edu

***Abstract*— Recent technological advances have enabled SDRs to switch from one frequency to another at low cost, thus making dynamic multi-band access possible. On the other hand, recent advances in signal processing combined with those in antenna technology provide MIMO capabilities, thereby creating opportunities for enhancing the throughput of wireless networks. Both SDRs and MIMO together enable next-generation wireless networks, such as wireless mesh networks, to support dynamic and adaptive bandwidth sharing along time, frequency, and space. In this paper, we develop a new framework that identifies the limits and potentials of SDRs and MIMO. We characterize and analyze the maximum throughput that wireless networks can achieve when they are SDR-capable and MIMO-equipped.**

I. Introduction

Recent advances in radio technologies have made it possible to realize SDRs (Software-Defined Radios) that, unlike traditional radios, can switch from one frequency band to another at no or little cost, thereby enabling dynamic and adaptive multi-band access and sharing. SDRs are considered as a key next-generation wireless technology to improve bandwidth utilization. On the other hand, recent advances in signal processing combined with those in antenna technology empowered wireless networks with MIMO (Multiple-Input Multiple-Output) or multi-antenna capabilities, thereby creating potential for network throughput enhancements via spatial reuse [1], [2] and/or spatial multiplexing [3], [4], [5]. Therefore, SDR and MIMO complement each other to form a complete means of enabling next-generation wireless networks with opportunistic bandwidth utilization along not only time and frequency via SDRs, but also space via MIMO.

Wireless mesh networks (WMNs) have also been considered as a key wireless networking technology for their advantages over traditional networks, such as low-cost, easy installation and maintenance, robustness, and reliability [6], [7], [8]. In addition to these capabilities, WMNs can still exploit SDRs and MIMO to increase total throughput, thereby improving spectrum efficiency even further.

In this paper, we develop a framework that identifies the limits and potential of SDRs and MIMO technologies in terms of the total throughput that they can provide to WMNs. This developed framework can be used to derive guidelines for designing and optimizing multi-band-capable, multi-antenna-equipped WMNs. While SDRs are used to enable WMNs with dynamic and adaptive multi-band access, MIMO systems are used to increase the spatial reuse of spectrum, and hence, the total network throughput. It is important to note that, although MIMO can be exploited to increase the overall network throughput via not only spatial reuse but also spatial multiplexing, we will focus on MIMO's spatial reuse capabilities, leaving the problem of exploiting MIMO to increase network throughput via spatial multiplexing as our future work.

Section II describes the network model, states our objective, and outlines the proposed approach. In Section III, we formulate the WMN routing problem, and propose a fast solution algorithm. Section IV identifies the maximum achievable throughput in WMNs. We finally conclude the paper in Section V.

II. Problem Statement

A. *Effective Degrees of Freedom (DoF)*

The degree of realizing spatial reuse benefits offered by multi-antenna systems is contingent on physical limitations such as a node's transmission/reception power, multi-path, and channel coefficient estimation errors. For instance, suppose m and n are two neighbor nodes, equipped with an antenna array of size π_m and π_n, respectively, and m wants to transmit data to n. Assume that there are φ communication streams currently being received by nodes located within m's transmission range, and ψ communication streams currently being transmitted by nodes located within n's reception range. Due to physical limitations, the number φ of nearby received streams that node m can prevent its signal, being sent to n, from reaching at is (1) not proportional to, and (2) likely to be less than its actual number of antennas π_m [9]. The number $\theta_m \equiv (\varphi + 1)$ is referred to as m's *effective transmit DoF* (1 corresponds to the communication stream from m to n). For similar reasons, the number $\vartheta_n \equiv (\psi + 1)$ of possible concurrent streams in n's vicinity, referred to as n's *effective receive DoF*, is (1) not proportional to, and (2) also likely to be less than n's total number of antennas π_n [9]. In [10], we derived a table-driven statistical method that allows each node m to determine both θ_m and ϑ_m given the network's physical constraints. We assume that nodes use this method to determine their effective transmit and receive DoFs.

B. *Network Model*

We assume that the radio spectrum is divided into multiple non-overlapping bands, and K is the set of these spectrum bands. A WMN is modeled as a directed graph $G = (N, L)$ with a finite nonempty set N of nodes and a finite set L of wireless data links. L is the set of all ordered pairs (m, n) of distinct nodes in N such that n is within m's transmission range. If $i = (m, n) \in L$, then m and n are referred to as the transmitter $t(i)$ and the receiver $r(i)$ of link i, respectively. A data link i is said to be *active* if $t(i)$ is currently transmitting to $r(i)$; otherwise, i is said to be *inactive*. For every $m \in N$, let $L_m^+ = \{i \in L : t(i) = m\}$, $L_m^- = \{i \in L : r(i) = m\}$, and $L_m = L_m^+ \cup L_m^-$. We assume that each node m is equipped with an antenna array of π_m elements, and let

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θ_m and ϑ_m denote the effective transmit and receive DoFs of m. For every $(i,k) \in L \times K$, let c_{ik}—which is assumed to be time-invariant—denote the maximum number of bits that link i can support in 1 second if communicated on spectrum band k.

Let C denote the set of all distinct ordered pairs $(i,j) \in L \times L$ such that (1) i and j do not share any node between them and (2) the transmission on link i interferes with the reception on link j when communicated on the same spectrum band. Note that $(i,j) \in C$ does not necessarily imply that $(j,i) \in C$. For every link $i \in L$, let $C_i^+ = \{j \in L : (i,j) \in C\}$ denote the set of all links whose receivers interfere with the transmission on i, and $C_i^- = \{j \in L : (j,i) \in C\}$ denote the set of all links whose transmitters interfere with the reception on i.

We assume that a node can either transmit or receive, but not both, at any time. We also assume that each link can be active on at most one band at a time. A link can, however, be active on two different bands during two different time slots. We consider the TDMA scheme to share the wireless medium. Time is then divided into time slots of an equal length. Let $T = \{1, 2, \ldots\}$ denote the set of these time slots. The throughput achievable under TDMA will then be viewed as an upper bound on those achievable under other multiple access methods such as CDMA and CSMA/CA. It is important to reiterate that our goal is to characterize the maximum achievable network throughput. That is, how to achieve this maximum throughput is of no relevance to our work, and so are the details regarding the TDMA scheme, such as time synchronization and overhead.

C. Objective and Approach

The objective of this work is to characterize and analyze the throughput that WMNs can achieve when they are (1) equipped with multiple antennas and (2) capable of communicating on multiple spectrum bands. To do so, we formulate the WMN routing problem as a standard multi-commodity instance, consisting of a set Q of end-to-end flows where each flow $q \in Q$ is characterized with a source-destination pair $s(q), d(q) \in N$, and a non-negative rate f_q. The WMN routing problem is then written as a packing LP whose objective is to maximize the sum of all flows, $\sum_{q \in Q} f_q$, subject to network constraints that we develop in [2] and summarize in Section III-A. The sum $\sum_{q \in Q} f_q$ will be used to signify the maximum achievable throughput under a multi-commodity flow f. We also propose a fast algorithm that finds a $(1-\epsilon)^{-2}$-approximation to the multi-commodity flow optimal solution (in minimizing the running time) that depends polynomially on ϵ^{-1}. The input parameter ϵ can be appropriately fixed so that a solution with acceptable quality can be obtained in polynomial time. By solving many instances, we can then identify and characterize the maximum throughput these WMNs can achieve.

III. Maximum Multi-Commodity Flow

A. Constraint Design

In our previous work [2], we described and modelled the radio and interference constraints on multi-hop wireless networks when they are MIMO-equipped, but not multi-band-capable. In this section, we present an extension of our previous work [2] to include multi-band access. (Since the focus of this work is not on deriving these constraints, we only provide a brief summary here—just enough to maintain the overall follow of the paper. Readers may refer to [2] for more details.)

Let's, for every $(i,k,t) \in L \times K \times T$, define the binary variable y_{ik}^t to be 1 if link i is active on spectrum band k during time slot t, and 0 otherwise. Now let's consider a set of time slots $S \subseteq T$ of cardinality $\tau = |S|$, and let's define ρ_{ik} as the continuous variable $\frac{1}{\tau}\sum_{t \in S} y_{ik}^t$ for all $i \in L, \forall k \in K$.

Radio Constraints: Under the assumption that (1) a link can only be active on at most one spectrum band at any given time slot, (2) a node can either transmit or receive, but not both, at any time slot, and (3) a node can use one DoF (degree of freedom) to transmit or receive a desired signal while using the other DoFs to allow for multiple simultaneous nearby communication sessions, one can write

$$\sum_{k \in K} \sum_{i \in L_m} \rho_{ik} \leq 1, \quad \forall m \in N. \tag{1}$$

Interference Constraints: Recall that, at any time slot, a receiver must have enough effective receive DoF to combat the interference caused by all nearby transmitters before receiving a signal, and a transmitter must have enough effective transmit DoF so that it can prevent its signal from causing interference to any nearby receivers prior to transmission. Hence,

$$\begin{cases} (M - \vartheta_{r(i)} + 1)\rho_{ik} + \sum_{j \in C_i^-} \rho_{jk} \leq M \\ (M - \theta_{t(i)} + 1)\rho_{ik} + \sum_{j \in C_i^+} \rho_{jk} \leq M \end{cases} \tag{2}$$

for all $(i,k) \in L \times K$. The above constraints ensure that the maximum number of active links that interfere with the transmission on link i does not exceed what node $t(i)$ can null, i.e., no more than $\theta_{t(i)}$ can be concurrently active at time slot t on the same spectrum band k when $t(i)$ is active. However, if $t(i)$ is not transmitting, then the constraints should be relaxed as expressed by the inequality via M.

B. Packing LP

We formulate the end-to-end multi-commodity flow routing problem as a standard packing LP. In the next section, we propose a fast algorithm for solving it. Let's consider a multi-band, multi-antenna WMN routing instance that consists of a set Q of commodities. For every $q \in Q$, let P_q denote the set of all possible paths between $s(q)$ and $d(q)$—a possible path in P_q is a sequence of (link,band) pairs between $s(q)$ and $d(q)$. By letting x_p denote the rate of a path p, one can write

$$\rho_{ik} = \frac{1}{c_{ik}} \sum_{q \in Q} \sum_{p \in P_q : p \ni (i,k)} x_p$$

for all $(i,k) \in L \times K$. Now, by replacing ρ_{ik} with the above expression in both the radio and interference constraints, Eqs. (1) and (2), the multi-commodity flow routing problem can be formulated as a standard packing LP as shown in Table I.

C. An Algorithm for Solving the Packing LP

We now propose a fast approximation algorithm for solving the packing LP. The idea is as follows. Instead of finding a solution to the packing LP problem, we propose

TABLE I

PRIMAL PACKING LP PROBLEM

$$\textbf{Maximize} \sum_{q\in Q}\sum_{p\in P_q} x_p \ \textbf{subject to:}$$

$$\sum_{i\in L_m}\sum_{k\in K}\frac{\sum_{q\in Q}\sum_{p\in P_q:p\ni(i,k)} x_p}{c_{ik}} \le 1, \quad \forall m\in N$$

$$(M-\theta_{t(i)}+1)\frac{\sum_{q\in Q}\sum_{p\in P_q:p\ni(i,k)} x_p}{Mc_{ik}} + \sum_{j\in C_i^+}\frac{\sum_{q\in Q}\sum_{p\in P_q:p\ni(j,k)} x_p}{Mc_{jk}} \le 1, \quad \forall(i,k)\in L\times K$$

$$(M-\vartheta_{r(i)}+1)\frac{\sum_{q\in Q}\sum_{p\in P_q:p\ni(i,k)} x_p}{Mc_{ik}} + \sum_{j\in C_i^-}\frac{\sum_{q\in Q}\sum_{p\in P_q:p\ni(j,k)} x_p}{Mc_{jk}} \le 1, \quad \forall(i,k)\in L\times K$$

$$x_p \ge 0, \quad \forall p\in P_q, \forall q\in Q$$

TABLE II

DUAL PACKING LP PROBLEM

$$\textbf{Minimize} \sum_{m\in N} u(m) + \sum_{(i,k)\in L\times K} v(i,k) + \sum_{(i,k)\in L\times K} w(i,k) \ \textbf{subject to:}$$

$$\sum_{(i,k)\in p}\left\{\frac{u(t(i))}{c_{ik}} + \frac{u(r(i))}{c_{ik}} + \frac{M-\theta_{t(i)}+1}{Mc_{ik}}v(i,k) + \sum_{j\in C_i^+}\frac{v(j,k)}{Mc_{jk}} + \frac{M-\vartheta_{r(i)}+1}{Mc_{ik}}w(i,k) + \sum_{j\in C_i^-}\frac{w(j,k)}{Mc_{jk}}\right\} \ge 1, \ \forall p\in P_q, \ \forall q\in Q$$

$$u(m), v(i,k), w(i,k) \ge 0, \ \forall m\in N, \forall i\in L, \forall k\in K$$

an algorithm that finds a solution to its dual. The dual of the packing LP is shown in Table II, and consists of finding weight assignments $u(m)$, $v(i,k)$, and $w(i,k)$ $\forall m\in N$ and for all pairs $(i,k)\in L\times K$ such that the sum of all weights is minimized while ensuring the shortest weighted path to be greater than unity. In matrix notation, the packing LP and its dual can, respectively, be written as $\max\{a^T x : Ax \le b, x\ge 0\}$ and $\min\{b^T z : A^T z \ge a, z\ge 0\}$ where $a^T = [1,1,\dots,1]$ is a vector of length $\sigma = \sum_{q\in Q}|P_q|$, $b^T = [1,1,\dots,1]$ is a vector of length $\omega = |N| + 2\times|K|$, and A is a $\omega\times\sigma$ matrix whose positive elements can be extracted from Table I or Table II.

Our proposed approximation algorithm for solving the packing LP is given in Table III. The algorithm follows from the work in [11]. Let ϵ be a fixed positive number and $\delta = (1+\epsilon)[(1+\epsilon)\omega]^{-\frac{1}{\epsilon}}$. The algorithm starts off by assigning δ to all weights, and then proceeds iteratively. In each iteration, a *length* function $Z : L\times K \longrightarrow \Re^+$, which assigns each pair (i,k) the value $Z(i,k)$ (see Table III for the expression of $Z(i,k)$), is determined. The algorithm then computes the shortest weighted path among all pairs $(s(q),d(q))$, $\forall q\in Q$, where a path between a (source,destination) pair, $(s(q),d(q))$, is a set of (link,band) pairs that connect the source to its destination. A flow is then routed via this shortest path. The rate of this flow is chosen such that the minimum capacity edge belonging to the shortest path is saturated; the capacity of an edge e belonging to the shortest path p is $A(e,p)$. The weights of (link,band) pairs belonging to this path are increased as a result of this flow. The algorithm terminates when the sum of all weights is greater than or equal to unity.

Given $\epsilon > 0$, the proposed algorithm finds a $(1-\epsilon)^{-2}$-approximation to the multi-commodity flow optimal solution in running time that depends polynomially on ϵ^{-1}. The input parameter ϵ can be appropriately chosen so that a solution with acceptable quality is obtainable in polynomial time (trading off some precision for faster execution). The following theorem states the tradeoff between the solution accuracy and the running time of the algorithm. The proof follows from [11].

TABLE III

APPROXIMATION ALGORITHM

Initialize:
$u(m) = v(i,k) = w(i,k) = \delta, \forall m\in N, \forall(i,k)\in L\times K$
$f = 0$
While $(\sum_{m\in N} u(m) + \sum_{(i,k)\in L\times K}[v(i,k)+w(i,k)] < 1)$

- Assign each pair $(i,k)\in L\times K$ the number $Z(i,k) = \frac{u(t(i))}{c_{ik}} + \frac{u(r(i))}{c_{ik}} + \frac{M-\theta_{t(i)}+1}{Mc_{ik}}v(i,k) + \sum_{j\in C_i^+}\frac{v(j,k)}{Mc_{jk}} + \frac{M-\vartheta_{r(i)}+1}{Mc_{ik}}w(i,k) + \sum_{j\in C_i^-}\frac{w(j,k)}{Mc_{jk}}$.
- Find the shortest weighted path p^* among all paths between $s(q)$ and $d(q)$ for all $q\in Q$. Let l^* and n^* be the sets of all (i,k) and all nodes forming p^*.
- Write the expression $\sum_{(i,k)\in l^*} Z(i,k)$ in the form $\sum_{m\in n^*}\lambda_m u(m) + \sum_{(i,k)\in l^*}[\mu_{ik}v(i,k) + \nu_{ik}w(i,k)]$. Let $r^* = \max_{m\in n^*,(i,k)\in p^*}\{\lambda_m, \mu_{ik}, \nu_{ik}\}$.
- Assign:
  $u(m) \longleftarrow u(m)(1+\epsilon\frac{\lambda_m}{r^*}), \forall m\in n^*$
  $v(i,k) \longleftarrow v(i,k)(1+\epsilon\frac{\mu_{ik}}{r^*}), \forall(i,k)\in p^*$
  $w(i,k) \longleftarrow w(i,k)(1+\epsilon\frac{\nu_{ik}}{r^*}), \forall(i,k)\in p^*$
  $f \longleftarrow f + \frac{1}{r^*}$

EndWhile
Compute approximated throughput: $\hat{\eta} = \frac{f\epsilon}{1+log_{1+\epsilon}\omega}$

Theorem 1: ***For any fixed*** $\epsilon, 0<\epsilon<1$***, the proposed algorithm, shown in Table III, finds a throughput solution*** $\hat{\eta}$ ***to the packing LP, described in Table I, that*** (1) ***satisfies*** $(1-\epsilon)^2\eta^* \le \hat{\eta} \le \eta^*$ ***where*** η^* ***is the optimal***

solution, and (2) ***completes in*** $\omega\lceil\frac{1}{\epsilon}log_{1+\epsilon}\omega\rceil \times \mathcal{T}$ ***where*** $\mathcal{T}$ ***is the time needed to compute the shortest path.***

IV. Throughput Evaluation

We randomly generate WMNs, each consisting of $|N|$ nodes, each of which is equipped with an antenna array of π elements. Nodes are uniformally distributed in a cell of size $100m \times 100m$, where two nodes are considered neighbors if the distance between them does not exceed d meters. We assume that $c_{ik} = 1$ for all $(i,k) \in L \times K$. For each random WMN, $|Q|$ (source, destination) pairs are randomly generated to form $|Q|$ multi-commodity flows.

Our proposed approximation algorithm is solved for each WMN to find the maximum achievable throughput by the $|Q|$ commodity flows. The approximation parameter ϵ is set to 0.05. Hence, the approximated solutions, computed using the approximation algorithm, are found to be within 10% of their exact values. All data points in all figures represent averages over all of the generated WMNs. We ran simulations until the measured average throughput converges to within 5% of real values at a 98% confidence level.

A. General Throughput Behavior

Figs. 1 and 2 show the maximum achievable normalized[1] throughput as a function of the number of antennas (Fig. 1) and the number of bands (Fig. 2). Note that as the number of antennas and/or bands increases, the maximum achievable throughput first rises and then flattens out asymptotically. Let's, for example, consider the case when the number of bands equals 1 (see Fig. 1). Augmenting the number of antennas from 1 to 6 increases the normalized network throughput by a factor of 5.6 (from 1 to 5.6), whereas augmenting it from 6 to 12 increases the network throughput by only a factor of approximately 1.1 (from 5.6 to 6.7); the normalized network throughput is bounded by a factor of 7 as the number of antennas increases. A similar behavior is observed when the number of bands is increased from 1 to 25 while fixing the number of antennas, as depicted in Fig. 2. Recall that multiple bands and/or multiple antennas are capable of increasing the network throughput by allowing multiple communications to occur simultaneously in the same vicinity. For instance, multi-antenna-equipped nodes can use their antennas to suppress undesired signals sent by nearby transmitters, allowing them to receive interference-free signals concurrently with nearby transmitted signals. Likewise, multi-band-capable nodes can choose and switch to idle spectrum bands, also allowing them to avoid interference with nearby signals. Intuitively, it can then be concluded that the more antennas and/or spectrum bands a node can use, the more nearby transmitters' signals can be nulled, and hence, the higher the achievable network throughput. However, because nodes of a given network have a fixed number of interfering nodes, increasing the number of antennas and/or bands beyond that of a node's fixed number of interfering nodes can no longer increase the throughput of the network. This explains the asymptotic upper bound on the maximum throughput as a function of the number of antennas and/or bands.

[1]Normalized w.r.t. the achievable throughput when nodes are each equipped with one antenna and allowed to use one spectrum band only.

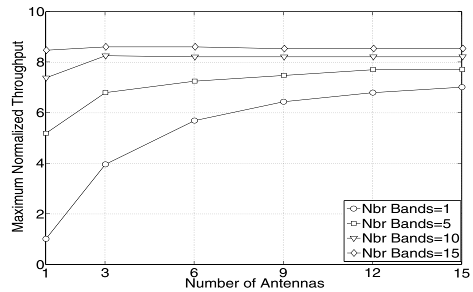


Fig. 1. The maximum achievable throughput as a function of the number antennas. $|N| = 50$, $|Q| = 25$, $d = 16m$.

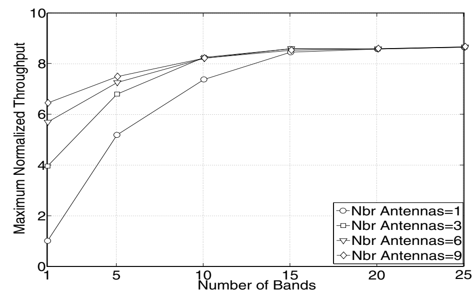


Fig. 2. The maximum achievable throughput as a function of the number of bands. $|N| = 50$, $|Q| = 25$, $d = 16m$.

In summary, given a WMN (i.e., defined by its node degree, connectivity, transmission range, etc.) and given the number of bands that nodes are allowed to communicate on, there is an optimal number of antennas beyond which multiple antennas can no longer increase the network throughput. Likewise, given a WMN and a number of antennas, there is an optimal number of spectrum bands beyond which the network throughput can no longer be increased with additional bands. Next, we will show how sensitive such optimal numbers are to the transmission range/power parameter.

B. Effects of Transmission Range/Power

We now study the effects of the transmission range on the maximum achievable network throughput. Recall that the greater the transmission range, the more the interference, but also the higher the node degree. While a higher node degree usually yields a more network throughput, more interference results in a lesser throughput. We would then like to study the extent to which, if any, such a trend holds when WMNs are both multi-band-capable and multi-antenna-equipped.

Fig. 3 shows the maximum achievable throughput (normalized) as a function of both the transmission range (in meter) and the number of spectrum bands when the number of antennas is 6 (Fig. 3(a)) and 12 (Fig. 3(b)). Throughout this subsection, we set the number of nodes $|N|$ to 50 and the number of multi-commodity flows $|Q|$ to 25. There are two important and useful trends to observe from the obtained results as discussed next.

1) Transmission Range/Power Optimality: Note that irrespective of the number of bands and/or the number of antennas, as the transmission range increases, the overall throughput keeps increasing until it reaches an optimal value after which it starts decreasing. In other words, for each combination of the number of bands and the number of antennas, there is an optimal transmission range at which the overall network throughput is maximized. Recall that the longer a node's transmission range, the more neighbors the node is likely to have. While a longer transmission range enables nodes to have more paths to route their traffic through, it also generates more interference for them to combat. On the other hand, shorter transmission ranges yield lesser interference, but also lesser path diversity. Therefore, when the transmission range is too short, although the resulting interference is relatively low, it is the lack of path diversity that limits the achievable throughput of WMNs despite their multi-band and multi-antenna capabilities. On the other hand, when the transmission ranges are too long, the interference dominates, thereby limiting the throughput. In this case, the multi-band and multi-antenna capabilities are not sufficient enough to suppress the extra interference caused by the long reach of transmitted signals.

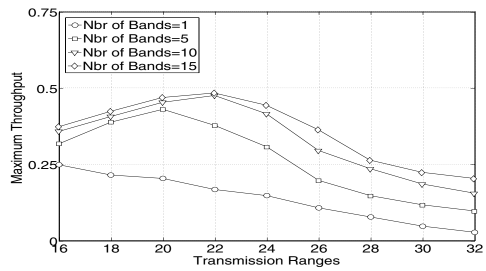
When the transmission ranges are appropriately chosen (neither too short nor too long), nodes can take advantage of the increased number of paths to find better routes while effectively combating the interference by using their multi-band and multi-antenna capabilities. In such a case, the throughput will be increased as more concurrent communication sessions are enabled in the same vicinity. This explains the convex behavior of the throughput as a function of the transmission range.

2) Transmission Range/Power Sensitivity: For any given number of antennas, the results show that the optimal transmission range at which the overall network throughput is maximized, keeps increasing as the number of spectrum bands increases. For example, when the number of antennas is 6 (Fig. 3(a)), the optimal transmission range is found to be 20 when the number of bands is 5, whereas it is 22 when the number of bands is 15. A similar behavior is observed (not shown in the paper) when the number of bands is fixed and the number of antennas is varied.

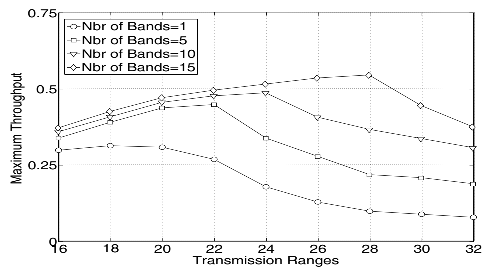
Recall that the multi-band and multi-antenna capabilities enhance the overall throughput of WMNs by allowing multiple concurrent communication sessions in the same vicinity. Hence, the more of these capabilities a WMN is empowered with, the more concurrent communication sessions it can allow, and hence, the higher the overall throughput it can achieve. However, providing a WMN with more capabilities than what could possibly be achieved in terms of number of concurrent sessions, does not increase the overall network throughput. The number of possible concurrent communication sessions for enhancing network throughput is determined by the number of neighbors the concerned nodes interfere with, which, in turn, is determined by the transmission range. As we discussed earlier, a longer transmission range corresponds to more possible concurrent sessions through higher path diversity. This explains why the higher the multi-band and/or multi-antenna capabilities a WMN is provided with, the longer the transmission range at which the overall network throughput is maximized, i.e., the higher the optimal transmission range/power.

V. Conclusion and Future Work

We proposed a framework that identifies the limits and potential of SDRs and MIMO technologies in terms of the maximum throughput that they can provide to WMNs. While SDRs are used in this study as a means of enabling WMNs with dynamic and adaptive multi-band access, MIMO is used as a means of increasing the spatial reuse of spectrum, and hence, the total network throughput. It is, however, important to note that MIMO can be exploited to augment network throughput not only via spatial reuse, but also via spatial division multiplexing. In the future, we intend to investigate and characterize the total throughput that multi-band, multi-antenna WMNs can achieve when MIMO benefits are exploited for spatial multiplexing.



(a) Number of antennas $= 6$



(b) Number of antennas $= 12$

Fig. 3. Effect of transmission range on throughput. $|N| = 50$, $|Q| = 25$.

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