A Framework for Joint Scheduling and Diversity Exploitation under Physical Interference in Wireless Mesh Networks*

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Abstract

Recently, interest has arisen in use of realistic interference models for transmission scheduling in wireless multihop networks, particularly in mesh networks where throughput is a major concern. In this work, we use the SINR-based physical interference model and develop a uniform framework for transmission scheduling when diverse wireless resources can be exploited. The factors considered are multiple (possibly overlapped) channels, directional antennas, and transmit power control. We develop an efficient heuristic for computing a diversity exploiting schedule based on a new network saturation metric. We prove that, under uniform random node distributions, the schedule produced by our heuristic is within a poly-log factor from optimal with a probability that approaches one as network size increases. Through simulation, we demonstrate the ability of our algorithm to achieve up to a 10-fold throughput improvement with respect to networks without diversity. Our analysis also reveals a number of insights on the ability of diversity exploitation to reduce or eliminate interference.

1. Introduction

Wireless mesh networks have the potential to provide ubiquitous broadband connectivity due to their ease of deployment and maintenance. However, their capacity is fundamentally limited by wireless interference [12]. A major goal of wireless networking research has been improving network capacity with sophisticated scheduling techniques that exploit various forms of diversity, such as channel diversity (multiple channels) and spatial diversity (e.g. transmit power control and directional antennas).

Scheduling-based schemes using TDMA have potential to allocate wireless channel resources in an optimal manner [27]. While TDMA-based scheduling has been widely studied (see Section 2), most of the existing literature uses a simplified view of wireless interference. Wireless interference is typically modeled as *hop-based* (potential interferers are within 1 or 2 hops from a receiver) or *distance-based* (potential interferers are within the 'interference range' of the receiver) or *distance-ratio based* (interference depends on the ratio of distances between sender-receiver and interferer-receiver pairs).

These models assume that (i) interference is 'binary' (interference either totally eliminates the ability to communicate or is non-existent), and (ii) interference occurs only between *pairs* of nodes or links. In reality, whether a communication is successful depends on whether signal power exceeds the sum of the interference powers plus noise by a threshold that is a property of the physical layer radio design. This SINR (signal to interference plus noise ratio)-based model is known as the *physical interference model* [12]. Note that interference is neither binary nor pairwise; aggregated interference from all communicating nodes must be considered to decide whether a communication is successful. Theory aside, recent performance studies with 802.11-based mesh networks also demonstrate that multiple interferers must be considered to evaluate interference limited capacity of a link [14].

TDMA scheduling using the protocol or simpler models has been considered widely in the literature. Depending on the exact model used, the problem is often NP-complete [23]; even sometimes hard to approximate within a polynomial factor [25]. However, use of realistic physical interference models has only recently begun [5, 6, 10, 20].

In this paper, we consider for the first time *multiple forms of diversity within a uniform framework in the context of a realistic physical interference model.* The goal is to increase significantly the throughput capacity of mesh networks. We consider both spatial diversity (using both transmit power control and directional antennas) and channel diversity (use of multiple, possibly overlapped channels). Current literature indeed has considered these diversities with TDMA (see Section 2), but only in an isolated fashion, and primarily with simpler interference models.

2. Related Work

Starting from Nelson and Kleinrock's work more than two decades ago [21], spatial reuse TDMA (STDMA) has been the standard MAC assumption in scheduling work in wireless multihop networks. The essential idea is that as long as there is sufficient physical separation, multiple transmissions can be scheduled in the same time slot. Al-

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most all existing scheduling algorithms assume hop-based, distance-based, or protocol interference. Some representative works of this type are [24, 26].

Prior work considered how to exploit individually channel, space, or transmit power diversity. The multichannel work often considers multiple radio interfaces per node. Channel assignment on interfaces or network links is addressed, sometimes jointly with routing and/or scheduling, e.g [1, 15, 17]. All of this work is based on protocol or hop-based interference models. Several papers have focused on transmit power control or directional antennas, e.g. [2, 16, 19, 22], but the focus was primarily on 802.11 MAC and the protocol interference model. There are some exceptions: [2] considers transmission scheduling and [19] considers the physical interference model.

Interest in TDMA scheduling under the physical interference model is fairly recent. Gronkvist and Hansson describe the use of physical interference in STDMA but do not provide an evaluation of the algorithm's time complexity nor compare its performance to optimal [11]. Moscibroda and Wattenhofer consider scheduling with physical interference under the assumption that traffic demands are the same on every network link and transmit power is unbounded [20]. The same problem, allowing arbitrary link demands, has been addressed in [4]. The authors of [5] present a heuristic for scheduling under the physical interference model and prove that, with probability approaching one, the schedule computed using this heuristic is at most a polynomial factor away from the optimal schedule for communication graphs produced from uniform random node distributions. In [6], a distributed scheduling algorithm that achieves the same bound as [5] is described. An SIR-based model, which fully considers interference but does not account for noise, has been used to study the complexity of optimally scheduling transmissions [10]. Existing works on scheduling with physical interference do not consider multiple channels nor directional antennas. Power control, however, has been considered in some instances [4, 20].

In contrast to all prior work, our work considers the three different forms of diversity jointly in a single framework under a true SINR-based physical interference model.

3. Network and Interference Models

A wireless mesh network is composed of n wireless routers (or *nodes*). Network deployments can be heterogeneous, i.e. some nodes might have directional antennas while others might have omnidirectional antennas, or only some nodes might be capable of transmit power control, etc. Radios operate on $C \geq 1$ channels, which can be partially overlapped. Directional antennas have up to $D > 1$ possible orientations. Nodes can select a transmit power from $P \geq 1$ power levels.

The communication graph is a graph $G = (V, E)$, where V is the set of routers, and $(u, v) \in E$ if and only if there is a channel/antenna orientation/transmit power assignment for u and v such that direct communication between u and v is possible in absence of interference. We assume that unidirectional links are not used by the network, so that edges in the communication graph are undirected.

Each edge e has a weight d_e, which represents the traffic demand on the link. d_e represents the aggregated traffic in both directions. The interference model defined in the following ensures correct message reception for both uplink and downlink transmissions. We are not concerned with how weights d_e are generated: our approach can be applied for arbitrary values of the weights. In practice, the demand on each link depends on the distribution and traffic pattern of wireless clients, and on the network's routing algorithm.

For an edge (u, v), let $P_v^{ijkhl}(u)$ be the received power at v of the signal transmitted by u, when u has a radio tuned on channel i and is transmitting with power level k and antenna orientation h, and v has a radio tuned on channel j with antenna orientation l. We use the value $h = 0$ ($l = 0$) to denote transmission (reception) with an omnidirectional antenna. Similarly, let $P_v^{i'jk'h'l}(w)$ be the received power at v of the signal transmitted by w, where w is a node that is transmitting while (u, v) is active, and w is transmitting on channel i' with power level k' and antenna orientation h'.

To account for possible transmission in both directions along link (u, v), we extend the physical interference model of [12] as follows: a packet sent along link (u, v) (in either direction) is correctly received if and only if:

$$\frac{P_v^{ijkhl}(u)}{N + \sum_{(x,y)\in E'} \max(P_v^{i'jk'h'l}(x), P_v^{i''jk''h''l}(y))} \geq \beta \ ,$$

and

$$\frac{P_u^{jik'''lh}(v)}{N + \sum_{(x,y)\in E'} \max(P_u^{i'ik'h'h}(x), P_u^{i''ik''h''h}(y))} \geq \beta \ ,$$

where N is the background noise, E' contains all links that have transmissions concurrent with the one on (u, v), and β is a constant threshold that depends on physical layer parameters such as desired data rate and modulation scheme. The above inequalities constitute the *correct reception condition* for (u, v). The max operator is needed since links can be operated in either direction during a time slot, and choices of direction are not coordinated. This model also allows for a reliable link layer protocol where ACKs are sent in reverse direction of data packets on the same links.

The conflict graph G_{Phy} is a multi-graph that has the same node set V as the communication graph, and a set of multi-edges associated with each node pair (u, v). The directed multi-edge $(u, v)_{ijkhl}$ has a weight w_{ijkhl}^{uv}, which represents the received power at node v of the signal transmitted by node u, when node u transmits on channel i with power level k and antenna orientation h, and node v has the radio tuned on channel j and antenna orientation l. Given multi-edges $(u, v)_{ijkhl}$ and $(v, u)_{jiklh}$, we might have $w_{ijkhl}^{uv} \neq w_{jiklh}^{vu}$, i.e. we do not assume a symmetric wireless medium. Note that the conflict graph concept is not dependent on any specific signal propagation model. In a deployed network, the weights could be generated based on measurements of actual channel characteristics [7].

The scheduling algorithm presented in Section 4 not only allocates sets of links scheduled to transmit in each slot, but it also decides, for each scheduled transmission e, the channel, transmit power, and antenna orientation assignment for e. Jointly performing resource allocation and scheduling (i.e., allocating resources on a per-slot basis) provides the maximum flexibility in exploiting diversity, which enables the highest possible throughput to be achieved.

From now on, unless otherwise stated, by transmission set we mean a set of $(transmitter, receiver)$ pairs enriched with channel/transmit power/antenna orientation assignment of nodes u and v. Given the communication graph $G = (V, E)$ and the conflict (multi-)graph $G_{Phy} = (V, E')$, we can determine whether a certain transmission set $E'' = \{e_1, \ldots, e_k\} \subseteq E$ is feasible as follows. Denote by $V(E'') \subseteq V$ the set of all nodes $u \in V$ such that u is the endpoint of at least one edge in E''.

Definition 1 *Given a communication graph $G = (V, E)$ and a conflict (multi-)graph $G_{Phy} = (V, E')$, a transmission set $E'' = \{e_1, \ldots, e_k\} \subseteq E$ is feasible under the physical interference model if and only if:*

$a)$ *E'' is a matching of G, and*

$b)$ *for every $u \in V(E'')$, with $e_i = (u, v) \in E''$ and $E_i = E'' - \{e_i\}$, the correct reception condition for (u, v) holds.*

Condition $a)$ is dictated by primary interference, and ensures that a node cannot transmit and receive on two different links in the same slot[1]. Condition $b)$ is dictated by secondary interference, and ensures that the SINR is above the threshold β at each node in $V(E'')$.

Concerning the complexity of building graph G_{Phy}, we observe that we have replaced a single edge in the model of [5] with up to PC^2D^2 multi-edges. Hence, the computational complexity of building G_{Phy} and verifying whether a certain transmission set is feasible is within a constant factor from the one of the original model, i.e. $O(n^2)$.

We are now ready to define the notion of *feasible schedule* under the physical interference model in our framework.

Definition 2 *Let G be the communication graph with traffic demands d_e on each link, and let G_{Phy} be the conflict (multi-)graph under the physical interference model. A schedule S composed of T_S time slots $t_1, \ldots, t_{T_S}$ is feasible for G if and only if the following conditions are satisfied:*

– *the transmission set scheduled at each time slot t_i is feasible under the physical interference model, and*
– *each link e is scheduled for at least d_e time slots.*

We consider how to compute a minimum-length feasible schedule, which is NP-hard even without diversity [10].

4. The DESP Scheduling Algorithm

We now present a heuristic for scheduling transmissions and allocating radio resources in wireless mesh networks under the physical interference model. The heuristic, called DESP (Diversity Exploiting Scheduler under Physical interference), has polynomial time complexity and, under certain assumptions, computes with high probability a schedule that is within a poly-log factor from optimal.

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Algorithm DESP:
Input: weighted communication graph G and conflict graph G_Phy
Output: a feasible schedule S of length T_S under physical interference
   and associated channel/transmit power/antenna direction settings

set available slots to ∅ and maxSlot to 0
order the links in E by decreasing traffic demand;
   let e_1, . . . , e_m be the resulting ordering
for i = 1 to m do
   set j to 1
   while j ≤ MaxSlot and d_{e_i} > 0 do
      set feasible to false and MM_min to ∞
      for each possible combination of channel, transmit power,
            and antenna direction on e_i
         if tx set in slot j is feasible with e_i added and
               given diversity settings then
            set feasible to true
            calculate MM value with new settings
            if MM < MM_min then set bestSet to current settings
      if feasible then
         record bestSet as settings for e_i in slot j
         set d_{e_i} to d_{e_i} − 1
   if d_{e_i} > 0 then
      add d_{e_i} slots at the end of the schedule and schedule
         e_i alone in these slots
      set maxSlot to maxSlot + d_{e_i}
      set d_{e_i} to 0
return schedule S with diversity settings, and length T_S = maxSlot
```

Figure 1. The DESP algorithm

DESP, which is described in Figure 1, is based on a greedy approach. Initially, links are ordered according to a certain metric (details later in this section). Then, links are considered sequentially and, for each selected link, slots currently in the schedule are scanned starting from the first one. A link e with weight d_e is inserted in the first d_e slots[2] such that adding e to the slot does not impair feasibility of the associated transmission set (as per Definition 1). If less than d_e such slots exist in the current schedule, new empty slots are created at the end of the schedule, and link e alone is allocated to these slots.

An important choice in DESP is the initial link ordering. Although the approximation bound proven in the next section is independent of the initial link ordering, from a practical viewpoint, the initial ordering has a substantial impact on performance. In [5], the authors suggest ordering links based on an estimation of the total interference induced by a given transmission, and scheduling the most interfering links first. However, in presence of diversity the amount of interference induced by a given transmission depends on the channel/transmit power/antenna orientation settings of the nodes, and the concept of 'most interfering link' is no longer meaningful. For this reason, in DESP, we have decided to order links from highest to lowest traffic demand.

A crucial choice when scheduling with diversity is how to assign channel, transmit power, and antenna orientation for each scheduled link. The idea we use in DESP is to define a metric accounting for *network saturation*, and to allocate resources based on this metric. Intuitively speaking, network capacity is maximized when *every slot* in the schedule is *close to saturation*, i.e. the SINR at each sched-

[1] This is true only in the single-radio setting.

[2] Here, we are assuming that traffic demand is expressed as a multiple of the amount of data that is transmitted in a slot.

uled receiver is close to the minimum threshold β for correct message reception. In fact, under these conditions it is very unlikely that other concurrent transmissions can be allocated to the slot. Hence, if all the slots in a schedule are close to saturation, schedule length is likely to be close to the minimum, and capacity should tend to be maximized.

The following is used to measure network saturation.

Definition 3 *Let $S = \{e_1, \ldots, e_k\}$ be the transmission set currently allocated to a certain slot. For any link $e_i = (u, v) \in S$, define $\delta_{e_i} = \min\{SINR_u - \beta, SINR_v - \beta\}$, where $SINR_x$ is the SINR value measured at node x when all transmissions in set S are active. The Max-Min metric of transmission set S, denoted $MM(S)$, is defined as:*

$$MM(S) = \left(\max_{e_i \in S} \delta_{e_i}\right) - \left(\min_{e_i \in S} \delta_{e_i}\right) .$$

The criterion used to schedule one link with positive traffic demand at a time is as follows. For every slot currently in the schedule, the slot is said to be *feasible* for the currently considered link e if there exists at least one channel/transmit power/antenna orientation setting for e such that the resulting transmission set is feasible. For each candidate feasible slot, DESP checks all possible channel/transmit power/antenna orientation assignments on e for feasibility and calculates the MM metric for each. If the transmission set is feasible for at least one assignment, the link is assigned to the slot and the diversity parameters are set to the values that minimize the MM metric.

The rationale for using the MM metric is the following. If the MM metric of a transmission set is relatively low, all the SINR values measured at the intended receivers are exceeding β by approximately the same value. Observe that a low MM value does not necessarily imply that the network is close to saturation. In fact, there might exist situations in which the MM value is very low (i.e., the SINR values at the receivers are well balanced), but the SINR at the nodes is far above β, and the network is far from saturation. However, as new transmissions are added to a transmission set and the MM metric is minimized, the maximum of the δ_{e_i}s is likely to decrease. This is because when transmission along a new link e is added to a transmission set S, the SINR values at all nodes in S can only decrease. Hence, if we denote with $S' = S \cup \{e\}$ the newly formed transmission set, we have that $\max_{e_i \in S'} \delta_{e_i}$ can be higher than $\max_{e_i \in S} \delta_{e_i}$ only if δ_e is higher than $\max_{e_i \in S} \delta_{e_i}$. It is easy to see that this situation is unlikely to happen, if the new transmission set S' has been chosen in such a way that $MM(S')$ is minimized among all transmission sets with the same link set.

Observe that when a link $e_i = (u, v)$ is allocated to an empty slot, the MM value of the resulting transmission set $\{e_i\}$ is 0 for any channel/transmit power/antenna orientation setting. Hence, a criterion should be defined for making channel/transmit power/antenna orientation assignment in this situation. In order to put the network in the 'farthest possible from saturation' initial condition, it is reasonable to select (through exhaustive search) the channel/transmit power/ antenna orientation setting for nodes u, v such that δ_{e_i} is maximized. This is the criterion used by DESP when links are allocated to empty slots.

5. DESP **Analysis**

We now prove an approximation bound for DESP under uniform random node deployment, and show that DESP has polynomial time complexity. The approximation bound holds under the following assumptions: $a0)$ radio signal propagation obeys the log-distance path model with path loss exponent $\alpha > 2$; $a1)$ nodes can use transmit power control; however, the maximum possible transmit power P_{max} is upper bounded by a constant, i.e. $P_{max} \in O(1)$; $a2)$ nodes can use directional antennas; a very general model of directional antenna is used, where the antenna gain $g(\theta)$ is only a function of angle θ, and $g(\theta)$ has constant upper and lower bounds, g_{max} and g_{min}, respectively; $a3)$ the nodes' clocks are loosely synchronized to permit proper STDMA operation.Note that nodes are allowed to use different forms of diversity in any combination, subject to $a1$, $a2$.

The random uniform node distribution we consider is as follows: a number $n = (8 + \varepsilon)C \ln C$ of nodes is deployed uniformly at random in a square area R of side $l = \sqrt{C}$, where ε is an arbitrary positive constant; the transmission range of a node is normalized to $r_{max} = 1$. This differs from the classical model, which places an increasing number of nodes uniformly at random in a unit disk region [12]. The model used herein has a deployment region of increasing size to avoid the 'singularity at 0' problem[3] that is inherent in the unit disk model. Furthermore, the above node density is minimal to ensure connectivity with high probability (w.h.p.[4]). Due to space limitations, all proofs are omitted, but can be found in [3].

Lemma 1 *Assume the random uniform scenario, and let u be an arbitrary node in the network which is at the receiver end of a communication link. The interference generated by nodes located at distance $d > s$ from u, where $s \geq 2r_{max}$, is w.h.p. upper bounded by*

$$C(\alpha) = \frac{6f(C)P_{max}g^2_{max}}{s^{\alpha-2}} \cdot \frac{2^{\frac{\alpha}{2}}}{2^{\frac{\alpha}{2}} - 2} ,$$

Theorem 1 *If $s = h(n)$, for some arbitrary function $h(n)$ of n such that $\frac{\log n}{h(n)} \to 0$ as $n \to \infty$, then $C(\alpha) \to 0$ as $n \to \infty$ w.h.p., and the SINR value at an arbitrary receiver u can be approximated with asymptotically negligible error (w.h.p.) by the SINR computed ignoring interference generated by nodes at distance greater than s from u.*

Theorem 2 *Let G be a communication graph with given link demands. Let T_{opt} be the minimum possible value of T such that a schedule of length T is feasible for G under the physical interference model, and let T_D be the length of*

[3] This occurs when sender-receiver distance asymptotically vanishes, which causes received power in the SINR formula to approach ∞.

[4] Herein, w.h.p. means probability $\to 1$ as $C \to \infty$.

the schedule computed by DESP. *Under assumptions* $a0$–$a3$*, and assuming the random uniform scenario, we have* $\frac{T_D}{T_{opt}} \in O(\log n \cdot (h(n))^2)$ *w.h.p., where* $h(n)$ *is an arbitrary function of* n *such that* $\frac{\log n}{h(n)} \to 0$ *as* $n \to \infty$.

Note that the approximation bound of Theorem 2 represents a significant improvement over the best prior bound for physical-interference-based scheduling, which was a polynomial (sub-linear) function of n [5]. Furthermore, this best previous bound applied only to scheduling with physical interference and did not include consideration of multiple channels, power control, and directional antennas.

Theorem 3 *Let* $G = (V, E)$ *be a communication graph with traffic demands* d_e *on each link; let* $n = |V|$*,* $m = |E|$*, let* $TD = \sum_{e \in E} d_e$ *be the total traffic demand in the network, and assume that the number* C *of available channels, the number* P *of available transmit power levels, and the number* D *of available antenna orientations are arbitrary constants. Then, Algorithm* DESP *executed on* G *has* $O(m \cdot TD \cdot n^2)$ *time complexity.*

6. Simulation-Based Evaluation

In this section, we report the results of the extensive simulations we have performed to investigate the relative benefits (in terms of throughput) of channel, transmit power, and antenna orientation diversity with physical interference.

6.1. Simulation Setup

To evaluate DESP's performance, we need a model for interference across overlapping channels that includes transmit power control and directional antennas. In our simulations, we assumed that radio signal attenuation between a transmitter u and a receiver v located at distance d is given by:

$$P_{uv}(d) = C_{uv} \cdot D_{uv} \cdot P(d) \tag{1}$$

where C_{uv} is a constant depending on channel separation, D_{uv} is a constant governed by the relative orientation of u and v's antennas, and $P(d)$ is the attenuation of the radio signal with distance, which is assumed to obey log-normal shadowing. C_{uv} varies over $[0, 1]$, and is set according to the measurements for 802.11b links reported in [8].

For directional antennas, we used the model of [22]. This model characterizes a directional antenna with two constants: g_{max}, which expresses the signal gain (with respect to an omnidirectional antenna) in the direction of the main lobe, and g_{min}, which expresses the signal gain in the sidelobes. Sidelobes are assumed to span all directions outside of the main lobe beamwidth. The relative values of constants g_{max} and g_{min} depend on the beamwidth, with a lower beamwidth resulting in higher g_{max} and g_{min}. We assumed nodes use switched beam directional antennas with 40 degrees beamwidth and 16 possible antenna orientations, and associated mainlobe and sidelobe gain of $14\ dB$ and $-7.6\ dB$, respectively (see [22]). In our simulations, we assumed that directional antennas can be used also on the receiver side, with similar gains.

Parameter	Urban	Rural
no. of nodes	100	100
deployment	square grid	uniform random
node density	100–300m node spacing	10–25Km side of depl. area
no. of gateways	5–15	5–15
routing	shortest-hop	shortest-hop
node traffic demand	chosen unif. in [1,10]	chosen unif. in [1,10]
reference technology	802.11g	802.11b
link data rate	54Mbps	11Mbps
packet size	2KB	2KB
slot length	0.33msec	1.63msec
SINR threshold	22dB	10dB
background noise	-90dBm	-90dBm
tx power	200, 150, 100, 50 mW	200, 150, 100, 50 mW
nominal tx range at 200mW	500m	2.7Km
log-normal parameters	$\alpha = 3, \sigma = 6dB$	$\alpha = 2.5, \sigma = 4dB$
g_m (directional gain)	10dB	14dB

Table 1. Parameters of the two scenarios

The last term in equation (1) determines the attenuation of the transmitted signal with distance, and obeyed log-normal shadowing in our simulations. The path loss and variance parameters for shadowing were set according to different scenarios. We considered two scenarios, which model urban and rural environments. The main parameters of the two scenarios are listed in Table 1.

We fixed the number of nodes to 100, and varied node density by changing the size of the deployment region. A number GW of nodes were randomly selected as gateways, with GW ranging from 5 to 15. Disjoint shortest path trees rooted at the gateways were built, and used to route packets from a non-gateway node to a closest gateway.

Traffic demands were generated as follows. Each non-gateway node's internal demand (expressed as a multiple of the amount of data transmitted in a slot) was generated by selecting at random a number in the interval [1,10]. Demands were then accumulated as they flow to the gateway. Since there is a single path to a gateway for each node, cumulative link demands could be computed easily.

The reference technology was 802.11g in the urban scenario, and 802.11b in the rural scenario. The choice of 802.11b in the rural scenario was motivated by the need for longer transmit ranges in this setting. Note that the higher link data rate with 802.11g requires a considerably higher SINR value to decode the signal.

We assumed $2KB$ data packets, and a time slot length that accounts for transmission of a data packet and propagation delays. Finally, we observe the different features of RF propagation in the two scenarios. Note that the path loss and variance values selected for the urban scenario closely match the values reported in [7]. Scattering and shadowing also have a negative effect on the efficacy of directional antennas, which is reflected in the lower value of the directional gain g_m in the urban scenario.

For both scenarios, we evaluated the throughput provided by the schedule computed by DESP in the following configurations: 1) no diversity; 2) channel diversity only (C); 3) tx power diversity only (P); 4) antenna orientation diversity only (D); 5) channel and tx power diversity (C+P); 6) channel and antenna orientation diversity (C+D); 7) tx power and antenna orientation diversity (P+D); 8) channel, tx power, and antenna orientation diversity(C+P+D). For the purpose of comparison, we have also evaluated the throughput achieved under the primary interference model,

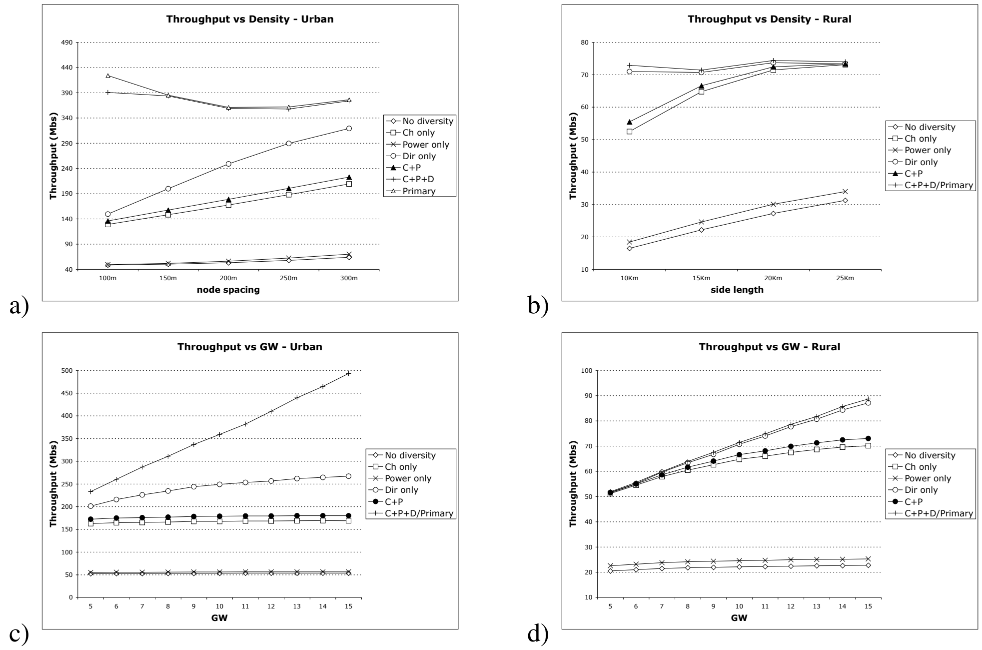

Figure 2. Network throughput for varying node density in the urban (a)) and rural (b)) scenarios. Network throughput for varying number of GW nodes in the urban (c)) and rural (d)) scenarios

which is computed according to [13].

Throughput is computed from schedule length, slot duration, and amount of data transmitted in a schedule. Thus, the values reported in the plots are slightly optimistic estimates of throughput, since throughput degrading factors such as clock skew, variability in signal strength, and so on, are not considered. However, in principle, these factors impact throughput independently of the degree of diversity exploited in the schedule. Hence, the *relative* throughput improvements of the different types of diversity with respect to the case of no diversity reported as a result of our simulations should not be affected by these factors.

For each setting of simulation parameters, we ran 500 simulations, and report the average value in the plots.

6.2. Varying Node Density

Figure 2 a)-b) reports throughput in the urban and rural scenarios for varying node density, with $GW = 10$. As seen from the figure, urban and rural scenarios display quite different behaviors with respect to diversity.

In the urban scenario, diversity plays a major role in improving throughput. While P diversity has a modest effect on performance (at most a 9.6% improvement[5]), both C and D diversity have a major effect. C (D) diversity can increase performance by up to 327% (500%). Even higher improvements can be achieved when different types of diversity are jointly considered. Performance with all 3 diversities combined can be improved by as much as 800%. As expected, diversity gives more advantages in denser scenarios[6].

A possible explanation of the modest effect of transmit power diversity on performance (which has also been observed to a lower extent in the rural scenario) is that the ratio of the maximum to the minimum power level available is $4 \approx 6dB$, which is very low compared to the SINR value required for correct message reception ($22dB$). On the contrary, directional antennas achieve considerable amplification of the transmitted signal ($28dB$), and channel diversity achieves a considerable attenuation of interference.

It is also worth observing that directional antennas are particularly helpful in the urban scenario: by exploiting only C+P diversity, the performance is at most 60% of the performance when all 3 diversity types are used. However, directional antennas come with additional hardware cost not incurred by the other diversities.

We also observe that the C+P+D curves reach a 'throughput limit' of the network, which cannot be further improved using diversity. This 'throughput limit' is dictated by primary interference, which cannot be mitigated by diversity (unless nodes are equipped with multiple radios, which is not considered in this paper). In fact, the throughput under primary interference is nearly identical to the one obtained with C+P+D diversity, except for the highest density scenario. This also indicates that DESP, when used in combination with full diversity, *achieves a performance virtually indistinguishable from optimal* (in the simulated scenarios).

The rural scenario displays both similarities and significant differences with respect to the urban scenario. Similarly to the rural scenario, P diversity alone has little effect on performance (up to 12% improvement), while C and D

[5] Unless otherwise stated in the following, by 'improvement' we mean 'improvement over the case of no diversity'.

[6] Note that in all the figures with varying node density, density increases when going left on the x-axis.

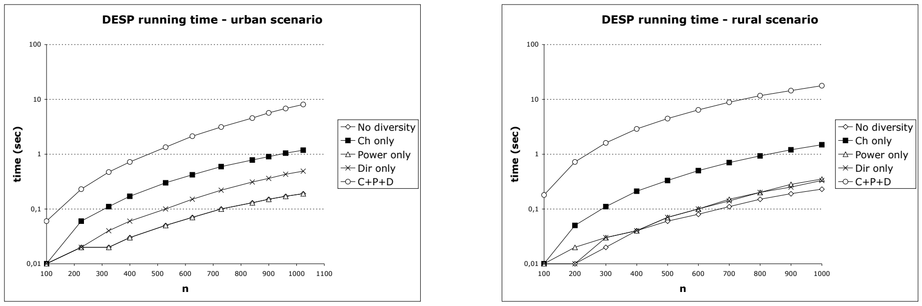

Figure 3. DESP **running time for varying number of nodes in the urban and rural scenarios**

diversity are much more effective in improving throughput, even when considered alone (up to 300% and 400% improvement, respectively). Full diversity achieves at most a 440% performance improvement in terms of throughput. Another similarity with the urban scenario is that throughput improvements tend to be larger for higher node densities. Finally, the 'throughput limit' dictated by primary interference can clearly be seen also in the rural scenario: in this case, the throughput obtained under primary interference is nearly indistinguishable (less than 1% improvement) from the one obtained under C+P+D diversity.

In contrast with the urban scenario, C+P diversity obtains almost the same performance as with full diversity: to be specific, C+P diversity achieves at least 93% of the C+P+D performance for medium to low node densities ($\geq 15Km$ of side length). Thus, at least in some situations, *costly directional antennas can be avoided with only a modest decrease in achievable network throughput*. We note, however, that in rural scenarios with very long-distance links, directional antennas might be required for increased transmission range. In these situations, the directional antennas can also be used to achieve (modest) throughput improvement. Another difference with respect to the urban scenario is that the relative advantage of exploiting diversity is more limited (up to 4.4-fold performance increase, in contrast with up to 8-fold increase in the urban scenario). We believe this notable difference in performance improvement is due to the irregular node placement and lower range of node densities considered in the rural scenario.

6.3. Varying Number of Gateways

In these experiments, we fixed node density to an intermediate value ($15Km$ of side length for the rural scenario, and $200m$ node spacing for the urban scenario), and varied the number of gateway nodes from 5 to 15. The results, which are reported in Figure 2 c)-d), clearly show the existence of two distinct interference regimes:

1) *secondary interference dominated regime*: when there is little or no diversity, secondary interference is the primary factor limiting performance. In this regime, *almost every link in the network is a bottleneck*, not only links close to the gateways. As a consequence of this, increasing the number of gateways has almost no effect on throughput. This phenomenon can clearly be seen for the 'no diversity' and P curves, in both the rural and the urban scenario. It is also worth observing that in case of no diversity, the throughput in the rural scenario is at most 22.7 Mbps, i.e. about twice the nominal capacity of a *single* link. This mean that, on the average, slightly more than two links are scheduled in a slot, with a very poor spatial reuse. The situation is even worse in the urban scenario, where the highest throughput in case of no diversity is 53 Mbps, i.e. *less* than the nominal capacity of a single link[7]. Hence, network nodes basically share a single radio channel, the resulting schedule is essentially sequential, and there is little or no spatial reuse.

2) *primary interference dominated regime*: in presence of a sufficient degree of diversity, secondary interference is negligible, and primary interference dominates. In this situation, adding more gateways is indeed useful, because with higher values of GW, the average length of paths connecting nodes to the closest gateway decreases, and the average degree of a gateway node (which is the only factor limiting GW throughput under primary interference) is reduced, with a positive effect on primary interference. This phenomenon can clearly be seen for the C+P+D curves, which grow almost linearly with GW and are indistinguishable from the curves obtained under primary interference. Note that in a primary interference dominated environment, spatial reuse is indeed very high: the highest throughput in case of full diversity is about 9 (8) times as much as the nominal capacity of a single link in the urban (rural), implying that, on the average, about 8-9 links are active in a slot.

Without enough diversity, the network is in an intermediate interference regime (C+P, C, and D curves). Finally, we observe that in the rural scenario, C+P diversity is not able to keep pace with full diversity when the number of gateways increases. Thus, directional antennas become more useful in the rural scenario as GW increases.

6.4. Other Evaluations

We considered the limited use of directional antennas, where only some nodes, e.g. gateways, were equipped with directional antennas and other nodes had omnidirectional antennas. The results showed that: 1) in the rural scenario, having 10% of nodes as gateways and equipping only gateways with directional antennas was sufficient to achieve a throughput nearly identical to the case where all nodes had

[7]Recall that slot length duration accounts for propagation delays in addition to data transmission.

directional antennas, and 2) in the urban scenario, equipping only gateway nodes with directional antennas produced about 10–40% reduction in throughput compared to the all directional case, but this still represented about 50-70% increase compared to the all omni-directional case.

We also considered the impact of delays in switching from one channel assignment to another and from one antenna orientation to another. With the TDMA slot sizes reported in Table 1 and switching delays of 0.1 msec for these two parameters, there was a 3% throughput drop in the rural scenario and a 15% drop for the urban scenario. Of course, the impact of these delays can be reduced by transmitting multiple packets in one slot, thereby increasing the slot duration. However, this also has the negative impact of increasing end-to-end packet delays.

Finally, we considered the average running time of Algorithm DESP, which is reported in Figure 3 for networks of intermediate node density and varying size. The algorithm was run on an Intel Core Duo E6600 processor with 1 GB of RAM. For practical network sizes ($n = 100$) and with all 3 types of diversity in use, DESP running time is only 0.18 sec in the rural scenario and 0.06 sec in the urban scenario.

7. Conclusions

In this paper, we introduced a unified framework for scheduling and diversity exploitation in wireless mesh networks based on a physical interference model. We also presented a heuristic based on a network saturation metric, which can be used to schedule communications exploiting different degrees of diversity (channel, transmit power, antenna orientation, or any combination). The proposed heuristic is very efficient in terms of running time, and, when exploiting full diversity, can be used to push network performance up to the limit imposed by usage of a single radio (primary interference). Implications of this could be substantial and deserve further consideration, e.g., tasks such as interference-aware routing and optimal GW placement could be significantly simplified if only primary interference need be considered.

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