

SPACE-MAC: Enabling Spatial Reuse using MIMO channel-aware MAC*

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Abstract—Smart antennas present a radical way to improve the capacity of wireless networks. The advantages of such antennas can be leveraged by the MAC and higher layers. In this paper, we present SPACE-MAC, a Media Access Control protocol for networks with smart antennas which enables “spatial reuse” of the medium by multiple transmit/receive pairs which are in the same collision domain. SPACE-MAC prevents interference between such pairs by selectively nulling the signals from potentially interfering transmissions. This is achieved in a totally distributed fashion utilizing channel state information (CSI) at both transmitter and receiver to adjust antennas weights for each packet transmission. As a difference from directional antenna MACs, which require near free space propagation conditions to achieve spatial multiplexing, SPACE-MAC can operate effectively also in cluttered (e.g., indoor) environments. As a difference from previous smart antennas MAC protocols based on nulling technique, SPACE-MAC achieves spatial reuse without requiring a separate channel for exchanging channel state information. This allows considerably better channel utilization. We investigate performance improvements of SPACE-MAC with respect to IEEE 802.11 DCF MAC using omnidirectional antennas.

Index Terms—MAC, Ad hoc networks, Spatial Reuse, MIMO, Beamforming, Wireless, Cross-layer.

I. INTRODUCTION

One of the most interesting trends in wireless communications in recent times is the proposed use of multiple-input multiple-output (MIMO) systems [2]. The use of multiple antennas at both transmitter and receiver provides enhanced performance over diversity schemes where either the transmitter or receiver, but not both have multiple antennas. MIMO can significantly increase the data rates of wireless systems without increasing transmit power or bandwidth usage thus enabling improved channel utilization and consequently system performance in wireless ad hoc networks. A MIMO link employs an antenna array at both ends of the link. In the most general MIMO configuration, the incoming data is demultiplexed into N distinct streams and each stream is transmitted out of a different antenna with equal power, at the same frequency, and with the same modulation and signal constellation. This is known as spatial multiplexing. It can achieve higher capacity on a single point to point link by maintaining multiple parallel streams. In this study we use

MIMO links in a more restricted fashion, namely, we transmit the same signal/stream, but weighted differently, out of each antenna element and exploit the array not to increase the throughput of a single transmit/receive pair but to enable reuse across pairs through proper beamforming [5] of the MIMO links.

Recently, several Media Access Control (MAC) protocols based on directional transmissions using antenna arrays in wireless ad hoc networks have been proposed [1], [4], [8], [10]. Directional transmission reduces interference and also facilitates spatial reuse, whereby multiple transmissions can take place simultaneously in the same collision domain [3]. However, directional transmission requires line of sight propagation. Indoor and urban outdoor environments are typically rich in scattering and possible line of sight blocking, multi-path conditions are prevalent. Multi-path propagation actually creates multiple channels and MIMO systems exploit this property to provide higher total capacity. However, these enhancements of the physical layer may not be efficiently utilized unless the MAC and higher layers are designed to exploit the features. Enabling spatial reuse using classic directional antennas to improve throughput in wireless networks has been proposed earlier [8]. In this study we argue for the use of MIMO beamforming links in a rich scattering environment, as this is a much more realistic condition in indoor and urban outdoor networks. The main contribution of this work is a fully distributed MAC protocol that exploits physical layer characteristics and cross-layer techniques to enable spatial reuse in scatter-rich multi-path environments.

SPACE-MAC uses channel information from the antenna arrays at each transmitter and receiver pair to implement transmit and receive antenna beamforming that achieves a threshold gain to the specified receiver while at the same time nulling of co-existing, potentially interfering transmitter and receiver pairs. The main advantage of SPACE-MAC with respect to conventional the 802.11 DCF MAC on which SPACE-MAC is based is that it allows multiple data streams at the same time in the same collision domain, thereby increasing, overall capacity of a network. The channel control overhead introduced by channel estimation and beam coordination is minimal and effectively countered by the gain provided by the increase in capacity of the MIMO channels.

A recently proposed MAC protocol based on MIMO type beamforming is NULLHOC [6]. One of the key features of

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that design is the division of the link layer bandwidth into two separate sub-channels for control and data respectively. This approach inherently limits the link layer bandwidth. SPACE-MAC protocol essentially achieves similar goals using a different design approach and in particular avoiding channel splitting.

The rest of the paper is organized as follows. Section II-A states the assumptions of the communication environment in which our MAC protocol is applicable. We then describe the channel state information exchange mechanism used by SPACE-MAC in Section II-C. Section III details our evaluation of the performance of SPACE-MAC using simulation. Finally, Section IV concludes the paper.

II. BASIC PROTOCOL OPERATION

A. Overview

We describe the design of a MAC protocol which exploits MIMO channel and smart antenna to enable simultaneous transmissions in a *single* collision domain. For example, in the situation illustrated in Figure 1, SPACE-MAC will allow Node A's transmission of a packet to Node C while Node B concurrently sends a packet to Node D. Figure 2 illustrates the abstract model of the adaptive antenna array with four antennas. Through out this paper, we use uppercase and lowercase boldface letters to denote matrices and vectors, respectively, and Superscripts T and H to denote the transpose operation and Hermitian operation, respectively. At the transmitter side, each antenna transmits the same signal after applying its own weight to the signal (e.g., in the figure Antenna 1 transmits $s(t)w_{T1}$). At the receiver, received signals from all antennas are individually weighted and summed allowing the output $r(t) = s(t) \mathbf{w}_T^H \mathbf{H} \mathbf{w}_R$ where \mathbf{w}_T is the weight vector $(w_{T1} \ w_{T2} \ w_{T3} \ w_{T4})^T$ of the transmitter, \mathbf{H} is the MIMO channel matrix between the two nodes, and \mathbf{w}_R is the weight vector of the receiver. (Channel coefficients and antenna weights can be represented as complex numbers.) Assuming N antennas at both the transmitter and receiver, we may represent the MIMO channel with an $N \times N$ matrix of channel coefficients \mathbf{H} where the h_{ij} element represents the channel gain between the i^{th} transmitter antenna and j^{th} receiver antenna as shown in Figure 2. In rich scattering environments such as indoor or urban outdoor, \mathbf{H} will be full-rank and can be characterized as a random matrix. The MIMO channel can be thought of as SIMO channel as shown in Figure 3. The effective channel then is $\mathbf{h}_T = \mathbf{w}_T^H \mathbf{H}$. We assume that coefficients of the effective channel can be estimated using standard methods. RTS and CTS MAC control frames shall carry training symbols for that purpose.

B. Antenna Weight Selection

To allow simultaneous multiple transmissions, both ends beamform, i.e., adjust weights, as follows:

- 1) Transmitter selects \mathbf{w}_T such that it does not affect any ongoing communications.
- 2) Receiver selects \mathbf{w}_R such that it receives only signal of interest and is not interfered by any other ongoing communications.

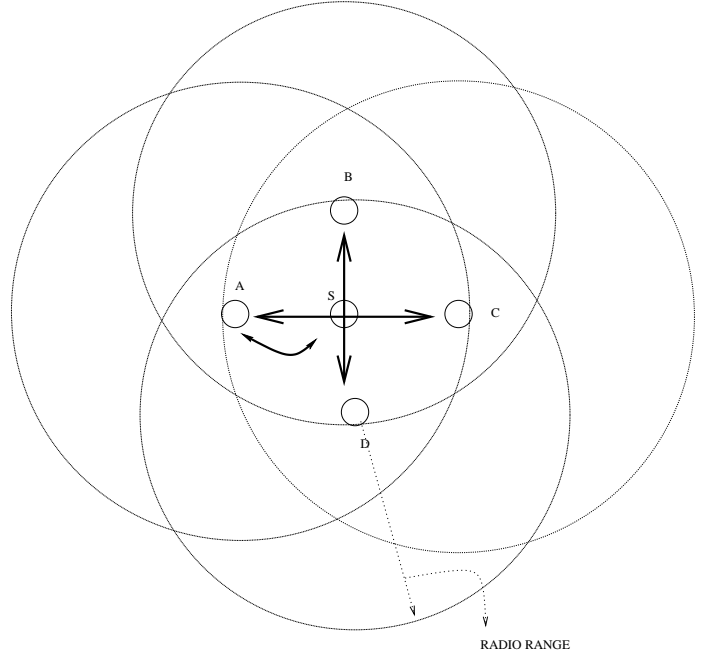


Fig. 1. Topology where SPACE-MAC enables spatial reuse.

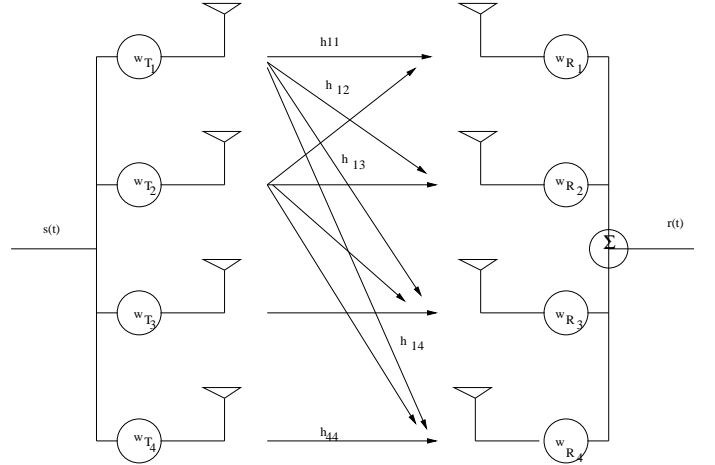


Fig. 2. Adaptive Antenna array system schematic with 4 antennas at the transmitter and receiver.

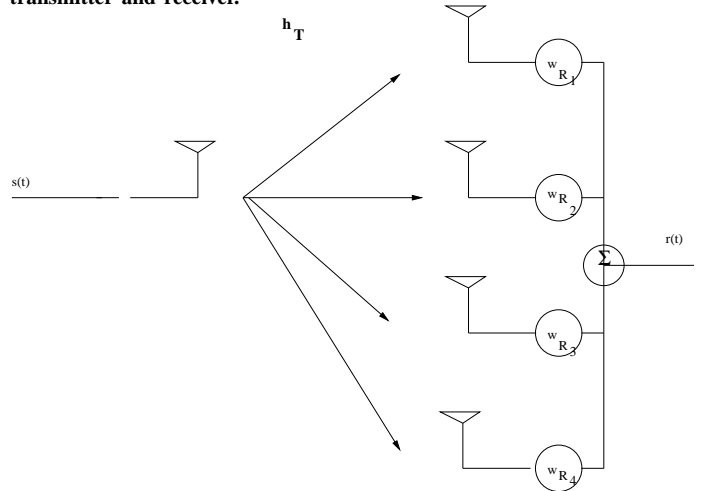


Fig. 3. Effective channel $\mathbf{h}_T = \mathbf{w}_T^H \mathbf{H}$

Let us consider a small network shown in Figure 1. Say at some point Node B wants to transmit a packet to Node D while Node C is sending a packet to A. If D can null the signal being transmitted from A to C and B transmits a signal which is nulled from A and C's perspective, we are enabling the two simultaneous transmissions. A node can null a signal easily if it knows the weight vector being used to transmit the signal. For example, D can null the signal from C by setting \mathbf{w}_D such that $\mathbf{w}_D^H \mathbf{H}_{CD} \mathbf{w}_D = 0$ where \mathbf{H}_{CD} is the channel matrix between C and D. Also, a node can generate a signal that is nulled from the perspective of a certain receiver if it knows the weight vector the receiver. For example, by adjusting \mathbf{w}_D such that $\mathbf{w}_D^H \mathbf{H}_{DA} \mathbf{w}_A = 0$, D can transmit a signal that means nothing to A. In our scenario, to accomplish the two simultaneous communications, A should know \mathbf{w}_B and \mathbf{w}_D where \mathbf{w}_B and \mathbf{w}_D are the weight vectors of B and D respectively and D should know \mathbf{w}_A and \mathbf{w}_C where \mathbf{w}_A and \mathbf{w}_C are the weight vectors of A and C respectively. This exchange of weight vectors is enabled by the MAC protocol described subsequently.

C. MAC Protocol Operation

Consider the topology as shown in Figure 1. Assume at the beginning all the nodes are silent, i.e., there is no on-going communication. A node which wants to transmit data to another node, say Node A, transmits a RTS using the default weight vector, $[\mathbf{1} \ \mathbf{1} \ \mathbf{1} \ \mathbf{1}]/\sqrt{4}$ in our 4-antenna example, or a random vector. The vector is normalized to have equal signal power regardless of the number of antennas. Note that different signal power results in different link performance. The weight vector used to transmit the RTS will be used to transmit the following data packet and to receive the corresponding CTS and ACK. Once the designated receiver of the RTS, say Node C, receives the RTS, it responds with a CTS packet using the current weight vector. The weight vector used for transmitting the CTS will be used to receive the following data packet and to send an ACK. The receiver estimates the SIMO channel vector $\mathbf{h}_{AC} = \mathbf{w}_A^H \mathbf{H}_{AC}$. In fact, as there is no on-going communication, Node C can switch its weight vector to $\mathbf{w}_C = \mathbf{h}_{AC}^T$ which maximizes the combined channel and array gain before it transmits a CTS. When a node other than the designate receiver receives a RTS, say Node D in our example, it estimates the effective channel \mathbf{h} and adjusts the weight vector such that the signal from the sender of the RTS is nullified (i.e., $\mathbf{h}_{AD} \mathbf{w}_D = 0$) for the duration of time specified in the RTS duration field. When a node other than the sender of the RTS receives the CTS, say Node S, it estimates the effective channel and stores the weight vector for the duration specified in the CTS duration field. After the RTS/CTS handshaking Node A sends and C receives a data frame using the weight vector \mathbf{w}_A and \mathbf{w}_C respectively chosen as described above. Note that the carrier sensing uses the signal $r(t)$ which is the output of the beamformer so the channel looks free is if there are only nulled signals on the air.

Now let us say B wants to initiate a transmission toward D. As it should ensure that the transmission between A and

C is not disturbed, it picks a \mathbf{w}_B satisfying two conditions, $\mathbf{w}_A^H \mathbf{H}_{AB} \mathbf{w}_B = 0$ and $\mathbf{w}_C^H \mathbf{H}_{CB} \mathbf{w}_B = 0$, before transmitting a RTS. Note that B already obtained $\mathbf{w}_A^H \mathbf{H}_{AB}$ and $\mathbf{w}_C^H \mathbf{H}_{CB}$ when it overheard A's RTS and C's CTS. B's counterpart, Node D, has to pick its weight vector such that the signal from A and C is nullified. D would already have done it when it overheard A's RTS and C's CTS so it either can use its current weight vector or select a new \mathbf{w}_D such that, as there is enough degree of freedom, the effective channel gain from B is maximized while any signal from/to A and C is nullified. This problem can be formulated as an optimization problem and using null-space projection it can be reduced to an eigenvalue problem in our case. Note that any additional new transmission is only possible if both the sender and receiver have enough degrees of freedom. As pointed out earlier that an N antenna system can null out at most $N - 1$ stations depending on environment. An N antenna system has N Degrees of Freedom (DOF) and every time a node nulls out another node, it consumes one DOF. In the scenario described in Figure 4, we assumed the nodes have 4 antennas each and hence a node can null out a maximum of 3 other transmitters so Node S should wait until A or B finishes their transmission. On reception of the RTS from B, S should estimate the effective channel from B while nullifying the signal from A. This is possible since what we need is not the exact channel vector but to find a weight vector that nulls both signals from A and B. Using some algebraic technique which is omitted in this paper due to the space limit, we can easily found the intersection of null spaces of the channels from A and B.

After a successful communication session, nodes are supposed to keep silent for a certain period of time specified in the field *silent_period* in RTS and CTS. During the course of communication, nodes are unable to track neighbors' activities. So they have to wait until the end of neighbors' activities started after theirs. Otherwise, they can disturb neighbors' communications. Imagine a situation where A and B are in the range of D but they are hidden terminals to each other and A just finished its communication session and D is receiving B's signal. A sees a clear channel but it doesn't mean there is no activity. A would have known D's activity if it was not engaged in its communication beforehand. In ad hoc networks with conventional radios and MACs, this kind of situation does not happen.

A node shall not start a new transmission if it cannot finish its transmission in the communication period (time to exchange RTS, CTS, DATA, and ACK) plus the silent period of any on going communication. The first sender, i.e., the node sees a clean channel, usually sets the silent period to half the longest packet time. The length of the silent period is an optimization factor and we empirically choose the above value. The second sender's silent period is the sum of the first sender's communication period and silent period minus its own transmission duration, which is known by the node in advance. After the silent period, it is recommended for nodes to switch to a random weight vector before it transmits an RTS. In fact, *silent_period* in RTS and CTS is the only SPACE-MAC's augmentation to 802.11 DCF MAC. All other specifics of SPACE-MAC are complaint to 802.11 DCF MAC otherwise

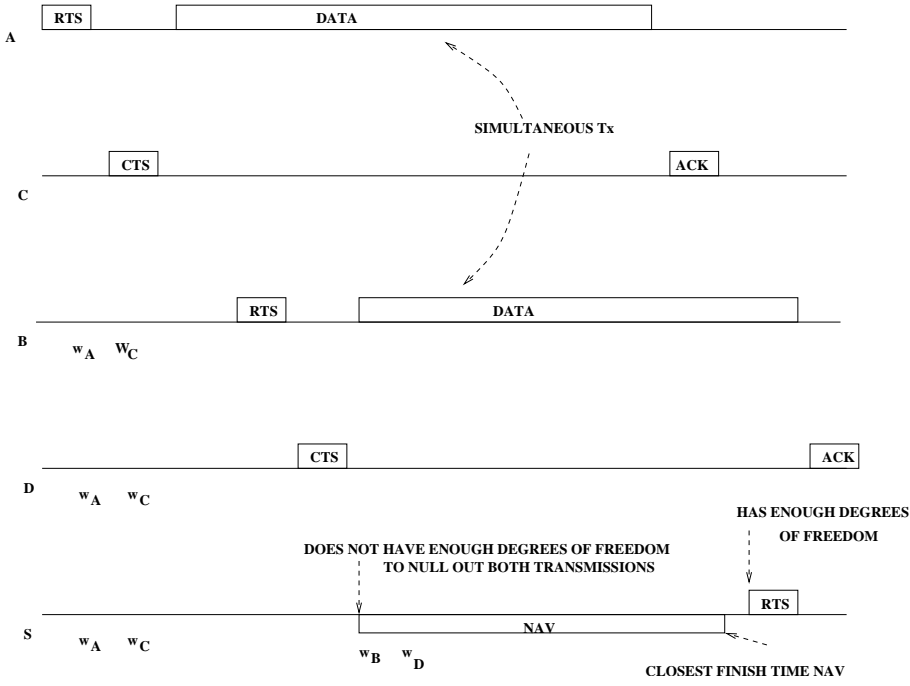


Fig. 4. MAC Protocol showing the mechanism of concurrent transmissions

specified.

When a node receives RTS or CTS, the node stores all the information delivered by it: the effective channel coefficient, and the duration of the session. This is necessary because a node may not have enough degree of freedom to null out interfering signals. When a node receives RTS or CTS and it is out of DOF, it sets NAV to the closest finish time of on-going session. When NAV expires we recalculate the weightvector. The process is explained graphically in Figure 4.

To summarize, SPACE-MAC is similar to the directional antenna system in that they accomplish spatial reuse based on the *source discrimination*. Obviously, the spatial reuse leads to the capacity gain of the network. The difference between our system and conventional directional antenna system is in the way the signals are discriminated. The directional antenna system discriminates the signals from their direction of arrivals (DOAs) whereas SPACE-MAC does the discrimination of signals based on their transmission weights.

III. SIMULATIONS

In this section we describe our simulation setup and present the results characterizing the performance of SPACE-MAC relative to IEEE 802.11 and NULLHOC in different scenarios. Our realization of SPACE-MAC in Qualnet [7] implements our protocol as explained in the earlier sections. Data structures holding antenna weights and channel information are added and gain due to the channel and the antenna array is calculated on the fly and applied to the computation of the Signal-to-Noise ratio (SNR) for each packet. The RTS and CTS frames are expanded 2 bytes to include *silent period* field. We assume that the channel estimation can be done with 802.11a/b/g PLCP preamble and no error in the channel estimation. We use the default values as Qualnet provides for

the configurable parameters (e.g., 15dBm transmission power) unless otherwise specified.

Our simulations assume a quasi-static Rayleigh fading environment [9]. The channel coefficient for each transmit-receive antenna pair is an i.i.d complex Gaussian random variable with zero mean unit variance and the channel is invariant during a complete session including RTS, CTS, DATA and ACK frame exchanges.

We run simulations for packet sizes of 512 and 1024 bytes. To evaluation of throughput, we compute a measure called normalized throughput which has been defined in [6] for the direct comparison to NULLHOC. Let M be the total number of data (excluding control frame) bits received successfully on a channel, T be the total simulation time and L be the link bandwidth. Then the *normalized throughput* is defined as $\frac{M}{T * L}$. The simulations were carried out using a link bandwidth of 2 Mbps. The normalized throughput that we computed measures performance independent of the link bandwidth. Not to be influenced by the higher layers, in our simulations we generate traffic at the MAC layer such that all nodes has always some data to send for a node in its radio range.

A. 20 node topology

We consider the scenario of a relatively dense network of 20 static nodes and all the nodes are in radio range of each other. Hence, in IEEE 802.11, only one collision-free transmission is allowed at one time. Assuming control overhead to be zero, the normalized throughput achieved by IEEE 802.11 DCF will be 1. As observed in simulations the normalized throughput of 802.11 and SPACE-MAC with different number of antennas and different packet lengths are shown in Figure 5 and Figure 6. Firstly, the IEEE 802.11 DCF achieves a normalized throughput of 0.7 and 0.8. The

drop in normalized throughput can be for several reasons such as the RTS/CTS and ACK exchanges as well as idle and backoff periods. Intuitively, the normalized throughput should increase with the number of antennas since the nodes will have more degrees of freedom to null out on-going transmissions. However the increase is not N -fold, where N is the number of antennas. Consider Figure 5, where 512 byte packets are sent. We observe that the normalized throughput increases to from 0.7 to 1 in the 3-antenna case. This is a 30% increase in throughput. For the 5-antenna case the gain is around 60% and for the 7-antenna case, the gain in throughput is over 80%. Typical hardware limitations might not allow the manufacture of a laptop or a mobile device with more than 5 antennas, hence we limit our simulations to the 7-antenna case.

SPACE-MAC does not achieve the expected maximum factor improvement of throughput because of the MAC control frame overheads. As the number of antennas increase this overhead increases. However the increase in throughput with respect to IEEE 802.11 MAC with NULLHOC for the 512 byte packet and a similar scenario is less. For example, NULLHOC achieves a gain in throughput of 30% for 5-antenna case which is less than the gain of around 60% that SPACE-MAC achieves. One of the reasons for this is the inherent limitation imposed by dividing the channel into sub channels for data and control. As the number of antennas increase this design limitation further hinders the achievable throughput in NULLHOC, since for a 7-antenna case, the gain in throughput of NULLHOC is less than 50% whereas for SPACE-MAC it achieves over 80% increase. Other reasons include more control frames and fixed longer silent time.

For larger packet sizes this overhead is even more pronounced. For packet size of 1024 as observed in Figure 6 the increase in throughput for the 5-antenna case in SPACE-MAC is close to 110% whereas for the NULLHOC it is around 65%. As observed with NULLHOC the throughput does not increase linearly in the number of antennas. This is because two degrees of freedom are needed to null an ongoing transmission and hence this observation is consistent with the throughput behavior observed with NULLHOC.

IV. CONCLUSIONS

In this paper, we have proposed a cross-layer MAC protocol termed SPACE-MAC exploiting MIMO channel for wireless networks. The proposed scheme nullifies the beam to competing nodes to enable concurrent transmissions in the same collision domain. Our approach is similar to [6] to the extent that we utilize the null steering approach. However the MAC design is more efficient since it does not limit the channel bandwidth by splitting the channel into control and data subchannels. Our simulation results confirm that SPACE-MAC performs better than NULLHOC as well as 802.11 DCF in all cases.

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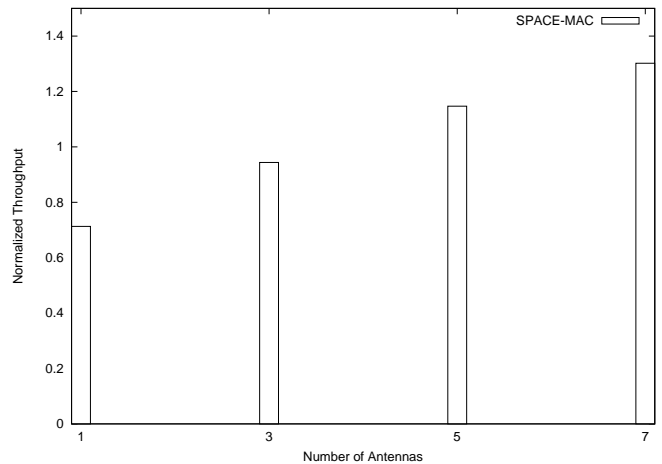


Fig. 5. Comparison of the normalized throughput of SPACE-MAC, IEEE 802.11 and NULLHOC with 512 Byte packets, with 20 node random topology with all the nodes in radio range of each other.

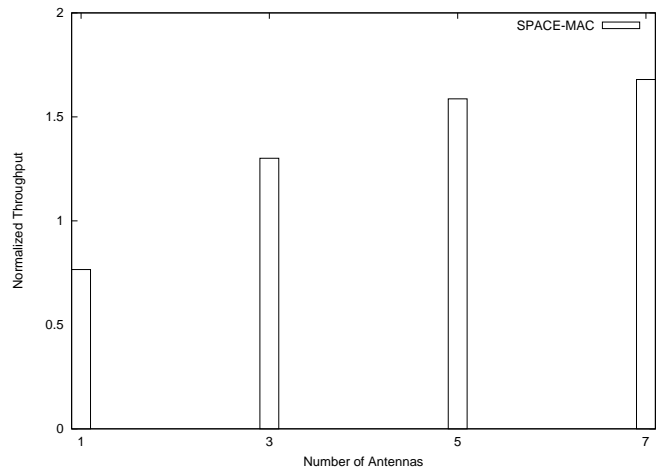


Fig. 6. Comparison of the normalized throughput of SPACE-MAC, IEEE 802.11 and NULLHOC with 1024 Byte packets, with 20 node random topology with all the nodes in radio range of each other.

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