Mobile Infostation Network Technology

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ABSTRACT

Inefficient use of network resources on the battlefield is a serious liability: if an asset communicates with the network command for data—a terrain map, for instance—it ties up the end-to-end network resources. When many such assets contend for data simultaneously, traffic is limited by the slowest link along the path from the network command to the asset. A better approach is for a local server, known as an infostation, to download data on an anticipated-need basis when the network load is low. The infostation can then dump data when needed to the assets over a high-speed wireless connection. The infostation serves the local assets over an OFDM-based wireless data link that has MIMO enhancements for high data rate and robustness. We aim for data rate in excess of 100 Mbps, spectral efficiency in excess of 5 bits/sec/Hz, and robustness to poor channel conditions and jammers. We propose an adaptive physical layer that determines power levels, modulation schemes, and the MIMO enhancements to use based on the channel state and the level of interference in the system. We also incorporate the idea of superuser: a user who is allowed preferential use of the high data rate link. We propose a MAC that allows for this priority-based bandwidth allocation scheme. The proposed infostation MAC is integrated tightly with the physical layer through a cross-layer design. We call the proposed infostation PHY, MAC, and network technology, collectively, as the Mobile Infostation Network Technology (MINT).

Keywords: Infostation, MIMO, OFDM, MINT, spectral efficiency, superuser, cross-layer, ad hoc, mobile, infrastructured.

1. INTRODUCTION

Consider this scenario: a doctor with a handheld viewer is on his rounds; the case files and updates that he needs—CAT scan images of a patient, for instance—potentially amounting to 100s of MBs are dumped onto his viewer as he passes through the doorway to the patient's room. The question is, what wireless technology can deliver such massive amounts of context-sensitive and time-sensitive information at a moment's notice? Conventional voice cellular model is based on the proposition that the value of a network—and hence the revenue potential for the network operator—is proportional to the square of the number of interconnected users: an implication of this value proposition is ubiquitous coverage at an "adequate" service level. A simple calculation reveals that the ubiquitous availability of adequate service is insufficient for "just in time" delivery of immense amount of data: if the network were designed for 1 Mbps over a large coverage area, a large number of users are covered, but at a data rate that translates to several minutes for the said doctor to download his data.

Infostations were proposed to provide islands of high data rate coverage [1, 2], as an alternative to the ubiquitous coverage model inherited from voice cellular systems: if data rate of the order of 100 Mbps can be achieved in a small area around the patients, where the doctor is expected to need his data, it only takes him a few seconds to download it. Inherent in this description is the notion that the combination of the doctor arriving at the patient's doorstep and the availability of the patient's data on the system gives the doctor greater claim on the system resources than the other users in the system.

The capacity of multihop wireless ad hoc networks has been established with and without mobility. Gupta and Kumar showed in [3] that, in a static network of *n* randomly distributed nodes, the throughput per source-destination

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pair, with the assumption that the sources chose their destination randomly, decayed in proportion to $1/\sqrt{n}$, despite the use of optimal scheduling and relaying of packets. Grossglauser and Tse extended this result to random mobility [4], and showed that the throughput per source-destination pair does not decay with the number of nodes n in the network when a two hop relay strategy is employed. In other words, the total network throughput grows at the same rate as the network size when the nodes are mobile. In related work by Diggavi, Grossglauser, and Tse [5], mobility was shown to help throughput even when constrained—even when the nodes were restricted to 1-D mobility, they were shown to achieve the same asymptotic throughput as that of 2-D mobility.

Unlike the multihop ad hoc networks considered in [3, 4, 5], infostation networks are "infrastructured" ad hoc networks with a centrally-scheduled last hop (from the infostation to the users), but the advantages of mobility are apparent. The concept of infostation was extended to mobile infostations [6, 7, 8], partly motivated by the theoretical throughput gains available with mobility and partly by applications that require mobile infrastructure—an application that requires a mobile infrastructure is the access of information on a battlefield. Consider the ground forces on an operation, not unlike the invasion of Iraq. Various entities in the unit may need access to different information, such as terrain maps, the day's plan, periodic information on enemy movement, and command directives. High resolution terrain maps and satellite pictures showing enemy movement are potentially large amounts of data, amounting to 100s of MBs. Mobile versions of the infostations, which are capable of providing extremely high throughputs, may be embedded in the unit to collect and store data on an anticipated need basis, which is then provided to the end users on demand.

Existing work on the capacity and performance of mobile infostation networks has focused on the network-level capability of the technology [6, 7, 8], without delving into its building blocks—the physical (PHY) and Medium Access Control (MAC) layer technologies. We present high-throughput PHY and MAC layer technologies that are ideally suited for high data rates and the provision of high-priority service for a certain class of users: a PHY based on MIMO-OFDM, and a MAC that performs centralized packet scheduling and allows for privileged superusers. In this paper, we provide an overview of the Mobile Infostation Network Technology (MINT) system architecture, and an explication of the MINT PHY and MAC technologies, whose performance we will elaborate in subsequent papers, along with updates on the performance of the MINT hardware prototype we are building.

2. MOBILE INFOSTATION NETWORK TECHNOLOGY (MINT)

Not all information is created equal—data can be differentiated by their sensitivity in time and location. Likewise, not all users are equal—they can be differentiated by their relative channel strengths and inherent importance. The conceit of MINT is that the combinations of data and users that score higher in relative importance have greater claim on the system resources. A high priority user-data combination must not only be able to avoid the general queue but also get a bigger chunk of the system throughput.

The central mechanism of MINT is the concept of superuser: a user who is designated by virtue of a combination of favorable channel state and a higher-layer priority mechanism as having a greater claim to the system resources. The higher layer priority mechanism may, for instance, rate the importance of different data types—a satellite image of enemy movement is clearly more important than a personal email with a large attachment—and conclude that users who are to receive the more time-sensitive data have a higher priority. Also, users with higher security designation may be deemed to have higher priority than those with lower security designation.

As shown in Figure 1, an infostation, one or more of which is present in the unit, is "filled" by satellites, UAVs, and whatever other means might be available at the theater. The fill stations are part of the backhaul network, which carries a variety of sensor data such as aerial pictures of enemy movement, and directives from the network command. The backhaul network consists of a variety of data links, both wired and wireless, and is usually limited by its weakest link. This limitation may be circumvented by judicious caching, a high-performance network technology, and a transport service that suits the application. For instance, a publish/subscribe network infrastructure may be used: the infostation keeps track of the interests of its users by maintaining an interest database and subscribes for information that meets these interests. The data publishers—for instance, the network command center—periodically publish description of the data they produce. The publish/subscribe network infrastructure will match the publishers and subscribers, and multicast new data to the relevant subscribers, i.e., the infostations, by use of a reliable multicast service optimized for the publish/subscribe infrastructure [9].

The infostation schedules the delivery of critical data immediately. Other data that were downloaded on an anticipated need basis are delivered when the demand arises. As shown in Figure 1, ordinary infostation users have a lower priority, lower throughput link with the infostation, whereas the superusers have a high priority, high throughput link. The infostation performs preferential scheduling. There may be multiple infostations within a unit for reliability and coverage, in which case the unit can be thought to be divided into clusters, each of which is served by an infostation. The clusters and the unit form the lowest rung of a hierarchy that extends through the backhaul network to the network command. A hierarchical key management infrastructure may be needed to provide flexible security across the tactical network, with multiple security levels [10]. The multiple security levels may also double as a measure of priority of the users.

There may be a dedicated channel for communication between the infostations in a unit, and this dedicated channel is used by an infostation to forward high-priority data for a high-priority user in a cluster served by a different infostation. An implication of this dedicated infostation-to-infostation forwarding channel is that not all infostations have to seek and store all information of interest that is available on the network—storage and processing load of the network is shared by all the infostations in the unit.

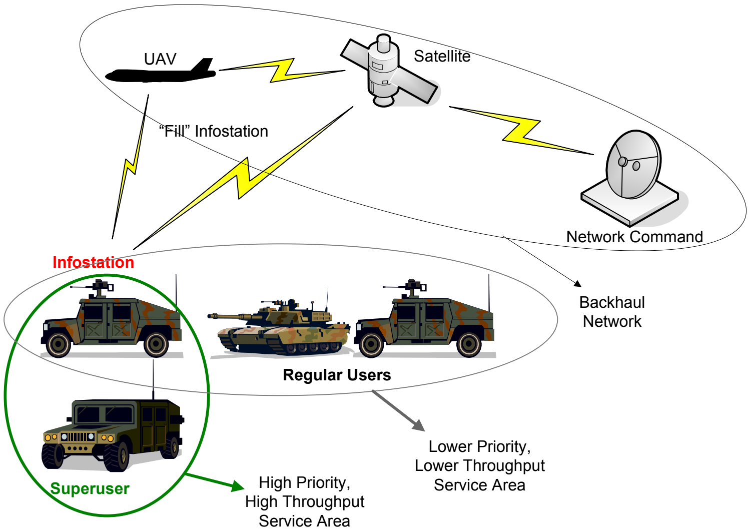

Figure 1—An illustration of the Mobile Infostation Network Technology (MINT) System.

3. PHYSICAL (PHY) LAYER

The MINT Physical layer (PHY) technology is Multi Input Multi Output – Orthogonal Frequency Division Multiplexing (MIMO-OFDM). Figure 2 is an illustration of the MINT PHY transmitter. Leaving out Spatial Vectorization and Spatial Processing, the MINT transmitter is roughly the equivalent of N_T OFDM transmitters in parallel, where N_T is the number of transmit antennas. Each of these OFDM transmitters is roughly the equivalent of an IEEE 802.11a/g transmitter. Spatial Vectorization parses the source data stream into a vector stream. Spatial Processing maps the (QAM) modulated vector stream onto a set of basis vectors.

The MINT PHY is similar to the High Throughput (HT) mode of the IEEE 802.11n PHY. The distinguishing features of MINT PHY are: innovative use of antenna resources to achieve optimal tradeoff between providing high throughput through spatial multiplexing, interference immunity through antenna-based antijam, and link stability through spatial diversity; dynamic rate determination; and a near zero-latency PHY-MAC interface, achieved through a cross-layer design, for fast adaptation of modulation, coding, and other PHY processing.

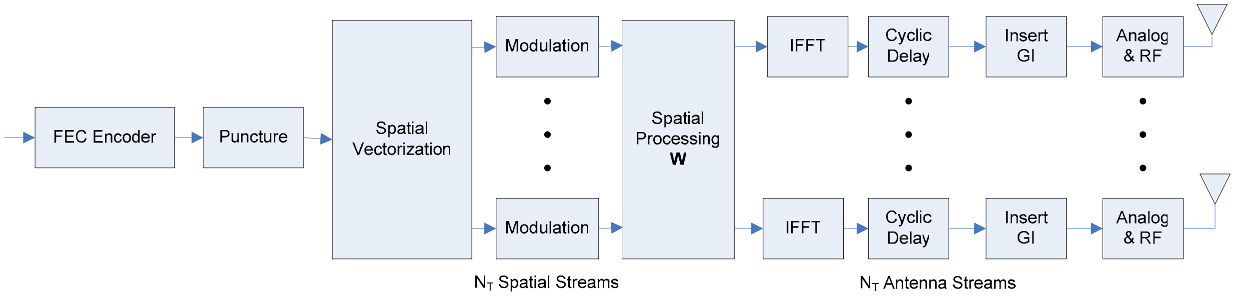

Figure 2—A Block Diagram of the MINT MIMO-OFDM PHY Transmitter.

If both the transmitter and the receiver possess Channel State Information (CSI), in the form of a MIMO channel matrix, the MINT transmitter can then optimally allocate its power over the eigenchannels [11]. If there are N OFDM subcarriers, then the MIMO-OFDM system devolves into N MIMO systems, one corresponding to each subcarrier. If the N subcarriers are divided into K groups, each of which share the same MIMO channel matrix (i.e., the subcarriers of the k^{th} group, for k = 1…K, are contained in the coherence frequency of the channel), then optimal power allocation may be performed across the K subcarrier groups as well as the eigenchannels of each subcarrier group. If the MIMO channel for the k^{th} subcarrier group is diagonalized as $\mathbf{H}(k) = \mathbf{U}(k)\sum(k)\mathbf{V}(k)^{\mathrm{T}}$, where $\sum(k) = \mathrm{diag}\{\lambda_i\}$, the optimal receive processing for any subcarrier in the k^{th} group is given by,

$$\hat{\mathbf{y}}(k) = \mathbf{U}(k)^T \mathbf{y}(k)$$

where,

$$\mathbf{y}(k) = \mathbf{H}(k)\mathbf{x}(k) + \mathbf{z}(k)$$

and, the optimal transmitter processing $\mathbf{x}(k) = \mathbf{V}(k)\mathbf{s}(k)$ for a source symbol vector $\mathbf{s}(k)$. In the preceding set of equations, an index to indicate an individual subcarrier within the k^{th} group is implicit.

A significant research opportunity in the PHY is a strategy for allocation of antenna resources between spatial multiplexing, diversity, and antijam. Spatial multiplexing impacts the PHY throughput; diversity impacts link stability; and antijam impacts the robustness of the system against jammers. There is a known mutual exclusivity between spatial multiplexing and diversity [12]; the practical implications of this in the context of the mobile infostation application are as yet not completely clear. The picture is further clouded by the use of antenna-based antijam to provide robustness against unintentional interferers and hostile jammers.

Figure 3 shows capacity in bps/Hz vs. SNR for different MIMO configurations for the MIMO-OFDM system. The antenna configurations shown are “square,” i.e., equal number of transmit and receiver antennas. We consider capacity with and without Channel State Information at Transmitter (CSIT). It is seen that the capacity with CSIT is more than double that of without CSIT. The channel model in Figure 3 is rich scattering, corresponding to a Ricean factor K = -50 dB. In this figure and the subsequent capacity figures, the channel is modeled as a MIMO channel with a specular component and a scattering component [13]:

$$\mathbf{H} = \sqrt{\frac{K}{K+1}}\mathbf{H}^{sp} + \sqrt{\frac{1}{K+1}}\mathbf{H}^{sc}$$

where,

$$\mathbf{H}^{sp} = \sqrt{G}\widetilde{\mathbf{H}}^{sp} \text{ and}$$

$$\mathbf{H}^{sc} = \sqrt{G}\widetilde{\mathbf{H}}^{sc}$$

G is the large scale path gain, which consists of path loss and shadowing effects. *K* is the Ricean factor. The components of the scattering matrix $\widetilde{\mathbf{H}}^{sc}$ are distributed as unit variance complex Gaussian random variables. The specular matrix is given by $\widetilde{\mathbf{H}}^{sp} = \mathbf{a}(\theta_t)\mathbf{a}^T(\theta_r)$, where $\mathbf{a}(\theta_t)$ and $\mathbf{a}(\theta_r)$ are the specular array responses at the transmitter and the receiver, respectively.

Figure 4 shows capacity in bps/Hz vs. SNR for different square MIMO systems for a channel with medium scattering (i.e., Ricean factor K = 0 dB). Just as in Figure 3, capacity with CSIT is more than double that of without CSIT.

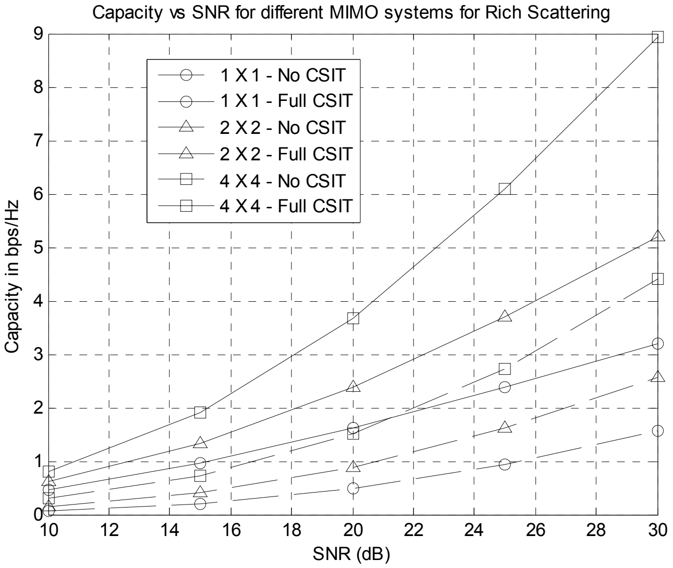

Figure 3—Capacity vs SNR for MIMO for Rich Scattering, with and without Channel State Information at Transmitter (CSIT).

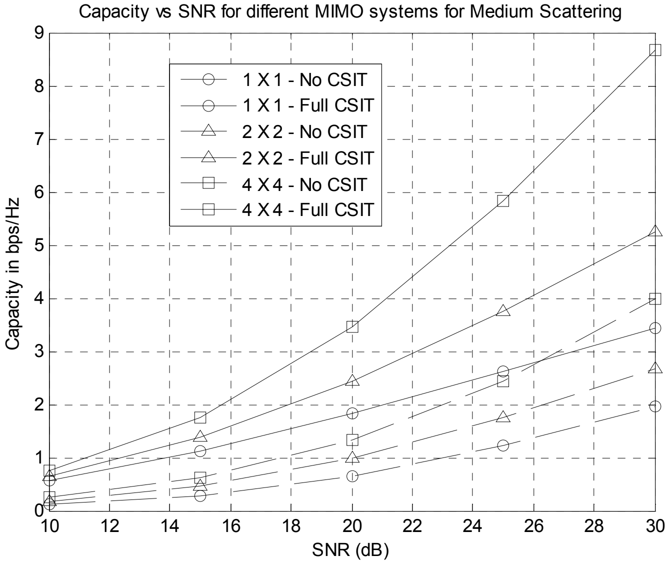

Figure 4—Capacity vs. SNR for MIMO for Medium Scattering, with and without Channel State Information at Transmitter (CSIT).

Figure 5 shows capacity in bps/Hz vs. SNR for the same square MIMO systems as in Figure 3 and Figure 4. The channel in this case, though, is Line of Sight (LOS), corresponding to a Ricean factor K = 50 dB. There is still significant gain in capacity with CSIT compared to without CSIT. But there isn't any difference in capacity between the different MIMO configurations when CSIT is known: with CSIT, the best performance is obtained by optimal power allocation over the eigenchannels, and when the channels are LOS, there is only one useable eigenchannel, immaterial of the MIMO system size. Without CSIT, though, the capacity for larger MIMO systems is higher than for smaller MIMO systems. This is because, although spatial diversity cannot be obtained due to the significant spatial correlation for LOS channels, the use of space-time diversity enables systems with more antenna resources to outperform systems with fewer antennas.

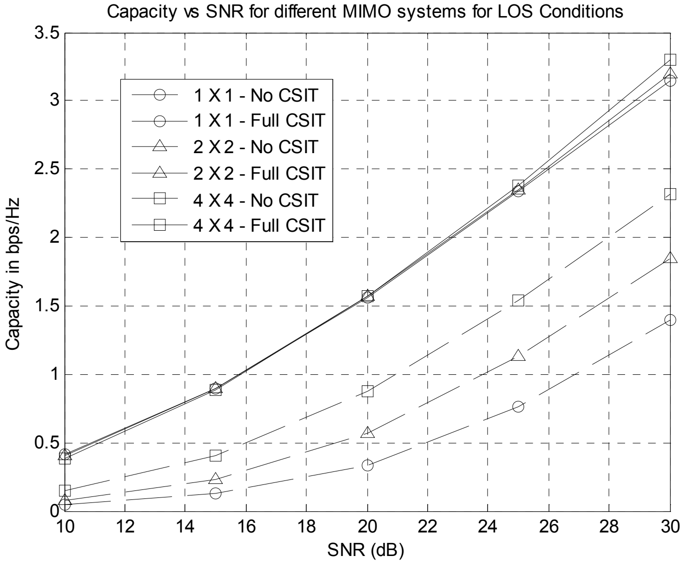

Figure 5—Capacity vs. SNR for MIMO for Line of Sight (LOS) channel conditions, with and without Channel State Information at Transmitter (CSIT).

4. MEDIUM ACCESS CONTROL (MAC) LAYER

The MINT MAC has a low-overhead and is designed to support high data rate communication between the infostation and the mobile users. It aims to achieve high throughput efficiency for large size file transfer. It supports high-priority superusers and performs centralized packet scheduling. Figure 6 shows the MAC-imposed temporal structure of the MINT data link, with alternating Channel Estimation Period (CEP) and Data Transmission Period (DTP). The durations shown in Figure 6 for the CEP and DTP, respectively, are 1-2 ms and 25-30 ms; typically, the choice of CEP and DTP durations are tailored to the expected channel coherence time, which is determined by the operating conditions and mobility profile, and the traffic profile, namely the characteristics of the applications and file sizes. A system with lower coherence time, in general, will require CEP more often than a system with higher coherence time. A system that is designed for larger file sizes could perhaps benefit from the allocation of an entire DTP to one user.

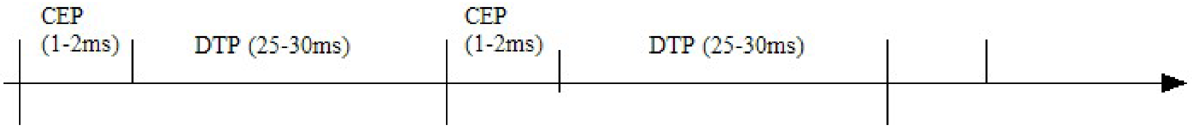

Figure 6—MINT MAC framing that shows the Channel Estimation Period (CEP) and Data Transmission Period (DTP).

Figure 7 shows the Channel Estimation Period (CEP) in greater detail. In infostation-controlled active channel estimation, the beacon will include a list of all users who have data waiting for them at the infostation—and if any data is deemed critical, a superuser qualifier is also attached to that user. When a user has uplink data to send to the infostation, he may commence user-initiated passive channel estimation (the passive here stands to mean that it is not controlled by the infostation). The users who wish to transmit or receive data provide their estimated channel to the infostation. A user who has been already designated a superuser may signal his intention to use the channel by sending a Channel Estimation (CE) frame during the non-contention miniSlot. The other users who need system resources transmit CE frames during the Contention Period (CP), which uses unslotted ALOHA. The end of CEP is indicated by the transmission of Channel Estimation End (CEE) frame by the infostation, which is separated from the CP by a Short Inter-Frame Space (SIFS).

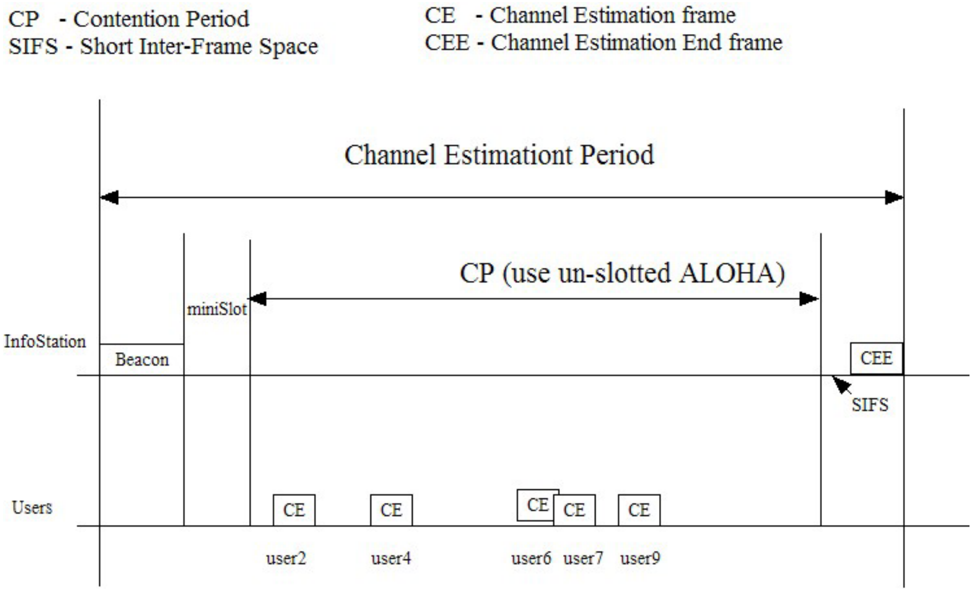

Figure 7—The Channel Estimation Period with a miniSlot reserved for the superuser and a Contention Period (CP) uses unslotted ALOHA for the other users.

Figure 8 shows the Data Transmission Period (DTP) in greater detail. The infostation may serve several users in each DTP based on pre-scheduling. Or it may serve only one user per DTP. A Block ACK (BA) mechanism with selective retransmission of erroneous subframes is employed. A Grant mechanism is used to control channel access during the DTP. Further improvements to the efficiency of the MAC protocol may include the use of one Grant frame to grant all users in a DTP, and the use of one ACK frame to acknowledge all uplink data.

The MINT MAC scheduling algorithm assumes that, via SVD, the MIMO channels are transformed by the PHY into parallel eigenchannels. The scheduling metric used by the MAC depends on the PHY transmission mode. For the basic mode, all eigenchannels use the same data rates. The achievable data rates are limited by the minimum eigenchannel gain. Therefore, the scheduling metric is to maximize the minimum eigenchannel gain, i.e., maximin of the channel matrix singular values. For advanced mode, each eigenchannel adopts different data rates based on its own channel gain. Therefore, the scheduling metric is to maximize the sum capacity of all eigenchannels, i.e., maximize the MIMO channel capacity. The superuser is scheduled first if the scheduling metric is greater than a threshold. After the superuser, the other users are scheduled if their metric, possibly used in conjunction with their coherence time (mobility), is greater than yet another threshold—the threshold for the regular users is higher than that of the superuser. For the regular users, the metric is also used to decide the order of transmission.

For a scheduled user, a simple strategy for dynamic rate determination is the counting of positive ACKs within a specified time window—if this number exceeds a threshold, the link can be bumped up to a higher rate; if, on the other hand, the ACK count falls below a different threshold, then the CSI is invalid if an order of time comparable to the coherence time has elapsed since the latest estimate, in which case channel estimation is triggered; but if the CSI is deemed valid, then the data rate of the link is bumped down.

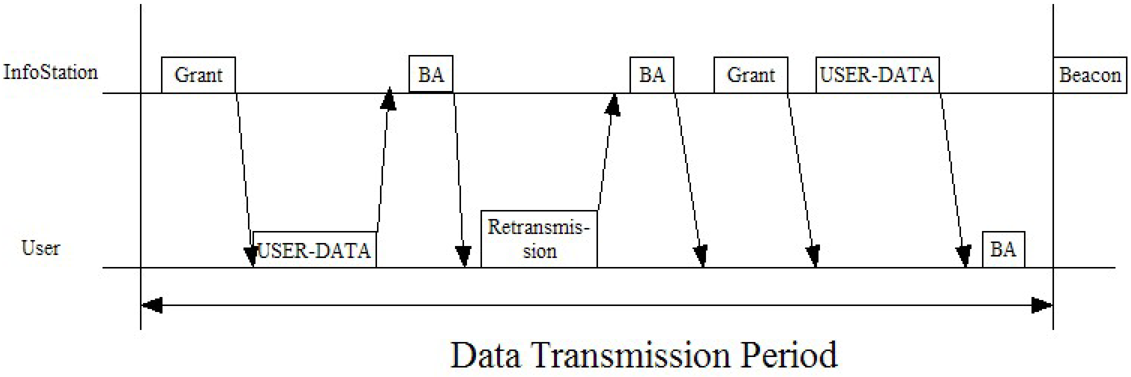

Figure 8—The Data Transmission Period (DTP) that shows the Block ACK (BA) mechanism for restransmission of select sub-frames in error.

Figure 9 shows the MINT MAC throughput for a 2x2 MIMO system compared to the throughput of an IEEE 802.11n- like MAC with the same channel model, PHY overhead, adaptive data rate scheme, and data frame size, as a function of the number of users. The data points for both throughput curves were generated using the network simulator NS2. The path loss model is two-ray ground propagation, but the users are all modeled to be received at average signal strength of 10 dB, implying a relative path loss of 0 dB. The entries of the 2x2 MIMO channel matrix are i.i.d. complex zero-mean Gaussian random variables with unit variance. A 40 MHz channel and baseline data rate of 13.5 Mbps is assumed, corresponding to the data rate achieved by a single eigenchannel with channel capacity of 1 bit per channel use and a coding rate of 1/2. The instantaneous data rate of the 2x2 MIMO system is then calculated as twice the channel capacity of the minimum gain eigenchannel (corresponding to the basic mode, which uses minimax scheduling metric), scaled by this baseline data rate. For the IEEE 802.11n system, adaptive data rate with channel estimation through RTS/CTS is assumed. In the single user case, the MINT MAC has less MAC overhead than IEEE 802.11n, and so outperforms it; for more users, the MINT MAC outperforms IEEE 802.11n by a wider margin due to multiuser gain. The simplistic data rate model used in generating Figure 9 likely does not provide accurate data rate results; nonetheless, it is a pliable model to measure the *relative* performance of the two MAC technologies.

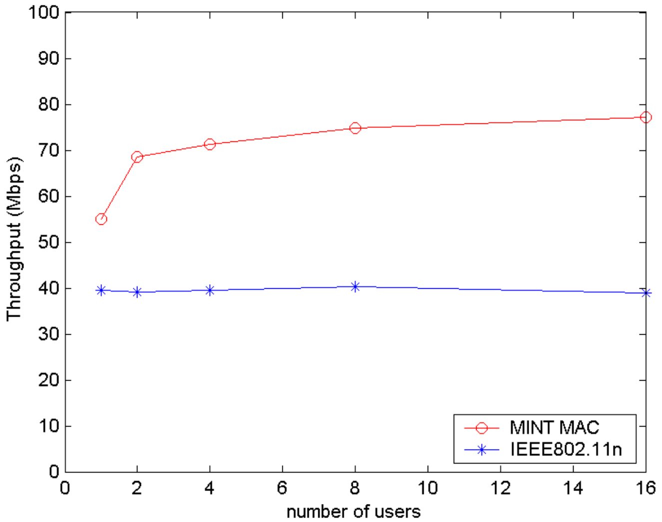

Figure 9—MINT MAC throughput for a 2x2 system in compared to the IEEE 802.11n-like MAC.

5. CONCLUSIONS AND FUTURE WORK

We presented Mobile Information Network Technology (MINT) system architecture for priority-based, high throughput data communication for tactical networks. We proposed PHY and MAC technologies for the infostations and the users in the MINT system, and presented preliminary performance results. A hardware prototype of the MINT system is currently under development. Future publications of this work will include performance of the MINT prototype, as well as the results of further research of the MINT PHY/MAC.

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