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Massive MIMO as a Cyber-Weapon

Marcus Karlsson and Erik G. Larsson

Abstract—A scheme for a multi-antenna jammer, jamming a SISO primary link working in TDD mode is presented. The jammer relies on reciprocity to estimate the channel to a terminal in the primary link blindly. The jammer can then beamform noise towards this user to degrade the performance of the primary link. Simulations show that, for certain scenarios, the proposed jammer can do the same damage to the primary link as an omnidirectional jammer, but with close to two orders of magnitude lower output power.

I. BACKGROUND

Massive MIMO refers to using large numbers, a hundred or more, of phase-coherently operating antennas at a wireless base station. This technology, originally conceived by Marzetta [1] is a game-changer in wireless access technology and has created a research area in which large progress has been made recently and which has attracted substantial academic and industrial sponsorship [2], [3]. Two tutorials that outline the main features of massive MIMO technology are [4], [5]. A paper that quantifies the potential of massive MIMO in a realistic multi-cell setup is [6].

The basic presumption of massive MIMO is that the base station can estimate the channel response to the terminals being served, by using measurements on uplink pilots. By exploiting channel reciprocity, these channel responses are then used in the downlink to perform multiuser beamforming. One of the main insights from the massive MIMO literature is that with M antennas, and estimated channels, the transmitted power (both on uplink and downlink) can be scaled down as $O(1/\sqrt{M})$ at a fixed information rate. Hence, when increasing M , the quality of the estimated channel state information gets worse and worse (because the SNR scales proportionally to $1/\sqrt{M}$), but this does not matter: the excess of transmitter antennas more than compensates for this loss of SNR. There is also substantial evidence that massive MIMO can be built with low-cost (low-accuracy) hardware [7]; hardware-induced distortion adds up “non-coherently” and the excess of transmitter antennas compensates for the increased hardware noise. Complexity-wise, massive MIMO with conjugate beamforming and TDD operation is entirely scalable: complexity (the computational operations and the amount of digital and RF hardware needed) is proportional to M .

Prototype implementations of massive MIMO already exist. The Argos testbed [8] has been successfully used to demonstrate that the beamforming gains predicted by theory hold true in practice, and additionally, that after appropriate

calibration, the assumptions on channel reciprocity hold. In the experiments documented in [8], 96 antennas were used. Another testbed underway [2] aims at using 100 antennas at a single base-station. Given current investments in massive MIMO (e.g., [2], [3]) it is likely that in a not-too-distant future, we will see many testbeds of this sort in full-scale operation—perhaps with even more antennas.

A. Vulnerable Wireless: the Jamming Threat

Jamming of wireless links represents a rapidly increasing, but seemingly less known cyber-security threat. Some examples are: jamming of private mobile radio (PMR) systems, used by police and other first responder personnel; jamming (and spoofing) of GPS receivers [9]; jamming of car lock remote controls in parking lots to facilitate easy theft of property; and jamming of wireless alarm systems in single-family homes to enable undetected burglary. Simple wireless jammers can be bought off the Internet for a few \$100, and equipment that used to be military-grade can be put together using off-the-shelf software radio-based platforms for a few \$1000. Numerous recent incidents, especially in public safety applications, illustrate the magnitude of the problem. During the EU summit in Gothenburg, Sweden, in 2001, activists used (illegal) jamming equipment located in a nearby apartment and during critical phases of the riots, the chief commander could not reach any of the 700 engaged police officers [10]. In addition, jamming against LTE, when used for PMR applications, is a growing concern [11].

Traditionally, jamming of wireless links has been considered a “military” problem, even though the awareness of the threat to civilian systems seems to be increasing. There may be a parallel with cyber-security on the Internet. Consider D-DoS attacks. They were not foreseen in the 1990’s—at least, the Internet and its protocols and servers were clearly not designed with this threat in mind—but this threat is now widespread and taken very seriously at all levels. It is not implausible that wireless jamming can undergo the same evolution, because: the harm that can be caused is substantial; society is relying more and more on wireless communications solutions; inexpensive, military-grade technology is proliferating; and the ability of an adversary to hide or to operate covertly is increased, for example due to the availability of cheap unmanned aerial vehicles (UAVs).

B. Contribution of the Paper

We demonstrate that if massive MIMO technology falls in the hands of adversaries, it can be used as a jamming device and cause significant harm to conventional wireless

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communication links that operate in TDD mode. The adversary must know the slot duration, but needs no other knowledge of the system to be jammed (such as channel state information, timing synchronization, pilot sequences or codebooks). Also, no “rank assumptions” on the propagation channels are needed. A TDD system is fundamentally sensitive to jamming attacks, because during transmission mode, it reveals its “location” so that an adversary could estimate the transmit strategy that would cause maximal harm. Some PMR systems—for example TETRA, used for police and firefighter communications—operate in TDD mode and hence are exposed to the vulnerability that we demonstrate here.

We quantify the extent of the harm that can be caused as functions of some key system parameters: number of antennas at the jammer; coherence time (determined by mobility); slot timing (determined by design of the primary system, must be less than the coherence time); and the distance between the primary system and the jammer.

II. SCENARIO

Conventional jammers spread the jamming signal omnidirectionally in order to jam a particular target. This is highly inefficient, because most of the output power will not reach the intended target and is therefore wasted. Since only a small portion of the output power is destructive to the target, very large output powers are generally needed. This huge output power and omnidirectional output makes the this type of jammer relatively easy to locate.

Directional jammers, such as the one presented in this paper, will need much less output power to be destructive to the primary link, due to the large number of antennas, M . The M antennas will make the jammer able to beamform “noise” to the target which provides an array gain over the omnidirectional jammer. Owing to the decrease in output power and the fact that most of the signal power is directed towards the target, a directional jammer is much more difficult to locate.

A. Primary System Transmission Scheme

Consider a system with two single antenna terminals, A and B, communicating in TDD mode over a narrowband, quasi-static channel with gain $h \sim \mathcal{CN}(0, 1)$. The coherence time T_C , over which the channel is essentially constant, is split equally between the two terminals. With a coherence bandwidth of B_C , the coherence interval is $\tau_C = T_C B_C$ complex samples.

The transmission scheme for the primary link can be seen in Figure 1. The k :th coherence interval is divided into two frames, A_k and B_k . During frame A_k terminal A transmits $\tau_C/2$ symbols, and during frame B_k terminal B transmits $\tau_C/2$ symbols.

Fig. 1. The transmission structure for the TDD link between A and B. Each coherence block k is divided into two frames, A_k , where A is transmitting, and B_k , where B is transmitting.

Let $T_0 \in \mathbb{N}$ denote the frame timing, the time (sample) when communication between A and B begins. The k :th coherence block is divided into A_k and B_k as

$$\begin{aligned} t \in A_k &\Leftrightarrow t - T_0 \in [(k-1)\tau_C, (k-1)\tau_C + \tau_C/2 - 1], \\ t \in B_k &\Leftrightarrow t - T_0 \in [(k-1)\tau_C + \tau_C/2, (k-1)\tau_C + \tau_C - 1]. \end{aligned} \quad (1)$$

The purpose of the jammer is to disrupt communication in one direction, say $B \rightarrow A$. This is done by beamforming noise to terminal A while terminal B is transmitting. In order to be able to beamform, the jammer must first estimate the channel to A, g_A . This has to be done every coherence interval. First, however, the jammer must estimate the frame timing, T_0 .

III. PROPOSED JAMMER

The general structure of the jamming scheme was mentioned in Section II-A and is explained in more detail here. To be able to jam the primary link, the jammer must:

- 1) Estimate the frame timing, T_0
- 2) Estimate the channel to terminal A, g_A
- 3) Beamform noise to terminal A

To estimate the channel to terminal A, the jammer relies on reciprocity; the channel from A to the jammer and the channel from the jammer to A, will be the same within a coherence block. This means that once B starts transmitting, the jammer can beamform noise in the direction of the channel it learned in the previous frame. The jammer has to estimate the channel every coherence block, while the frame timing is only estimated once.

A. Estimating the Frame Timing

Accurately estimating the frame timing is key to be able to do disrupt the primary link as much as possible. A poorly estimated T_0 will have two major effects, both of which degrades the jammer’s performance. The first is a “degree of freedom” loss, as the jammer loses jamming opportunity; the second is a degradation in the accuracy of the channel estimate. This will be explained in more detail in the end of Section III-A.

Since the transmitter in the primary link changes every frame, the channel the jammer sees will effectively change every frame. This change is what the jammer utilizes in order to estimate the frame timing. The $M \times 1$ received signal at the jammer in frame F is:

$$\mathbf{y}(t) = \mathbf{g}x(t) + \mathbf{w}(t) \quad (2)$$

where $x(t) \sim \mathcal{CN}(0, \rho_p)$ is the transmitted primary symbol at time t , $\mathbf{g} \sim \mathcal{CN}(0, \mathbf{I})$ is the channel, and $\mathbf{w} \sim \mathcal{CN}(0, \mathbf{I})$ is white (thermal) noise. To make notations easier, it is assumed that both of the primary terminals transmit with the same output power, ρ_p . To estimate T_0 , the jammer listens to K coherence blocks. Define the set of all frames $\mathcal{F} = \cup_{k=1}^K (A_k \cup B_k)$ and let $\mathbf{g}_F$ be the channel realization in frame F . Furthermore, let $\mathbf{y}_F(t) = \mathbf{y}(t)$, $t \in F$, i.e. the received signal in frame F .

Now, given the channel in frame $F \in \mathcal{F}$, the probability density function of the received signal in frame F is

$$p_{\mathbf{y}_F}(\mathbf{y}|T_0, \mathbf{g}_F) = \frac{1}{(2\pi)^M |\mathbf{Q}_F|} \exp(-\mathbf{y}^H \mathbf{Q}_F^{-1} \mathbf{y}) \quad (3)$$

where $\mathbf{Q}_F = \mathbb{E}[\mathbf{y}_F \mathbf{y}_F^H] = \rho_p \mathbf{g}_F \mathbf{g}_F^H + \mathbf{I}$. The likelihood function of T_0 for frame F is

$$L_F(T_0|\mathbf{y}_F(t), \mathbf{g}_F) = \prod_{t \in F} p_{\mathbf{y}_F}(\mathbf{y}(t)|T_0, \mathbf{g}_F) \quad (4)$$

To estimate T_0 the jammer listens for K blocks and constructs the likelihood-function

$$L(T_0|\mathbf{y}(t), \{\mathbf{g}_F\}_{F \in \mathcal{F}}) = \prod_{F \in \mathcal{F}} L_F(T_0|\mathbf{y}_F(t), \mathbf{g}_F). \quad (5)$$

Maximizing (5) is equivalent to *minimizing*

$$\begin{aligned} l(T_0|\mathbf{y}(t), \{\mathbf{g}_F\}_{F \in \mathcal{F}}) &\triangleq -\log L(T_0|\mathbf{y}(t), \{\mathbf{g}_F\}_{F \in \mathcal{F}}) \\ &= \sum_{k=1}^K \left(\sum_{t \in A_k} (\log |\mathbf{Q}_{A_k}| + \mathbf{y}(t)^H \mathbf{Q}_{A_k}^{-1} \mathbf{y}(t)) \right. \\ &\quad \left. + \sum_{t \in B_k} (\log |\mathbf{Q}_{B_k}| + \mathbf{y}(t)^H \mathbf{Q}_{B_k}^{-1} \mathbf{y}(t)) \right) + \text{constant}. \end{aligned} \quad (6)$$

The ML estimate of $T_0, \hat{T}_0$ is then found as

$$\hat{T}_0 = \underset{T_0}{\operatorname{argmin}} l(T_0|\mathbf{y}(t), \{\mathbf{g}_F\}_{F \in \mathcal{F}}) \Big|_{\mathbf{g}_F := \hat{\mathbf{g}}_F}, \quad (7)$$

where $\hat{\mathbf{g}}_F$ is the jammer's estimate of the channel in frame F . How the jammer estimates the channel is described in Section III-B. Since $\mathbf{Q}_F$ is unknown, the estimate $\hat{\mathbf{Q}}_F$ is used instead. For a given, hypothetical T_0 , the estimate of $\mathbf{Q}_F$ is the sample covariance matrix

$$\hat{\mathbf{Q}}_F = \frac{1}{|F|} \sum_{t \in F} \mathbf{y}(t) \mathbf{y}(t)^H, \quad (8)$$

where $|F|$ denotes the number of samples in frame F .

Note that the log-likelihood function in (6) will be (almost) periodic, since the jammer can only estimate the frame timing modulo $\tau_C/2$. The period of (6) will be $\tau_C/2$ samples, since that is the length of one frame. What parameters in the simulation that affect the likelihood-function will be covered in Section IV.

Remark: The accuracy of estimating T_0 will depend on the distance between terminal A and the jammer, as well as the output power of the primary link, ρ_p , since these factors determine the SNR of the received signal at the jammer. A higher output power will increase the achievable rate of the primary link, but also make the channel easier for the jammer to estimate.

Once T_0 is estimated, the jammer uses $\hat{T}_0$ to calculate the timing of all the frames according to (1), but with T_0 replaced with its estimate, $\hat{T}_0$. The estimate of frame F is denoted $\hat{F}$, see Figure 2.

The quality of the estimate of the frame timing T_0 determines the overlap between each frame and its corresponding estimate. As an example, assume we only have one coherence

block, divided into A and B . Furthermore, let $\hat{A}$ and $\hat{B}$ be the corresponding frame estimates and let $\bar{A} = A \cap \hat{A}$ and $\bar{B} = B \cap \hat{B}$. If $T_0 \neq \hat{T}_0$ the estimated frames and the correct frames do not coincide, i.e., $\hat{A} \neq A$ and $\hat{B} \neq B$ as seen in Figure 2.

Fig. 2. The difference between the actual frame timings (A and B), and the frame timings estimated by the jammer, $\hat{A}$ and $\hat{B}$.

$\bar{A}$ is the part of $\hat{A}$ during which the jammer listens to the correct terminal; the smaller $\bar{A}$ is, the worse the channel estimate will be. Similarly, $\bar{B}$ is the part of $\hat{B}$ during which the jammer beamforms to terminal A when terminal B is transmitting. The smaller $\bar{B}$ is, more time will be spent on trying to jam terminal A , when it is actually transmitting.

B. Estimating the Channel

The covariance matrix of the received signal in frame F is $\mathbf{Q}_F = \rho_p \mathbf{g}_F \mathbf{g}_F^H + \mathbf{I}$. This matrix has the eigenvalues $1 + \rho_p \mathbf{g}_F^H \mathbf{g}_F, 1, 1, \dots, 1$, and the eigenvectors corresponding to the eigenvalue $1 + \rho_p \mathbf{g}_F^H \mathbf{g}_F$ is $c \mathbf{g}_F$, for any $c \in \mathbb{C}$. The channel estimate $\hat{\mathbf{g}}_F$ is given by the eigenvector corresponding to the dominant eigenvalue of $\hat{\mathbf{Q}}_F$. The scalar ambiguity can be ignored in this case, as the jammer beamforms white Gaussian noise, the phase of the channel vector does not matter. During $\hat{B}_k$, the jammer will transmit $x_J = \sqrt{\rho_J} \frac{\hat{\mathbf{g}}_{A_k}^*}{\|\hat{\mathbf{g}}_{A_k}\|} s_J$, where ρ_J is the transmit power of the jammer, and $s_J \sim \mathcal{CN}(0, 1)$ are the noise symbols.

C. How Good is the Jammer?

To assess how good the proposed jammer is, a performance metric is needed. The metric chosen is the upper bound on ergodic capacity, which assumes coding across multiple coherence intervals:

$$\begin{aligned} R_{B \rightarrow A} &= \frac{T_{\bar{B}}}{T_B} \mathbb{E} \left[\log_2 \left(1 + \frac{\rho_p |h|^2}{1 + \rho_J |\mathbf{g}_A^H \hat{\mathbf{g}}_A|^2} \right) \right] \\ &\quad + \left(1 - \frac{T_{\bar{B}}}{T_B} \right) \mathbb{E} [\log_2 (1 + \rho_p |h|^2)]. \end{aligned} \quad (9)$$

The term inside the first expectation is an upper bound on the capacity of the primary link, when jamming is present. $\frac{T_{\bar{B}}}{T_B}$ is the fraction of time the jammer beamforms to terminal A , when terminal B is transmitting, i.e., when the jamming does damage, as discussed in Section III-A. The rest of the time is wasted by beamforming to A while A is transmitting. This means that for a fraction $\left(1 - \frac{T_{\bar{B}}}{T_B}\right)$ of the time, B transmits undisturbed, hence the normal SISO capacity expression in the second expectation.

IV. SIMULATIONS

There are a number of different parameters that affect the rate achieved by the primary link. All simulations use the path loss exponent $\alpha = 3.8$ and the normalized transmit power of the primary link, $\rho_p = 7$ dB is fixed. It is important to note that the value of ρ_p does not only affect the capacity of the primary link. The higher the transmit power of the primary link, the higher the SNR at the jammer, which leads to a more efficient beamforming, and therefore a higher degradation of the primary link when jamming is applied. That is, even though the capacity of the primary link without jamming increases with ρ_p , the capacity of the jammed link can actually decrease.

The relative distance, d_r , is the ratio between the distance between the terminals in the primary link and the distance from the jammer to terminal A. This parameter, similarly to ρ_p , affects the SNR at the jammer. The further away the jammer is, the worse performance of the jammer.

The number of coherence blocks, K , that the jammer listens to is also a parameter that affects the ability to accurately estimate the frame timing. The longer the jammer listens, the better the estimate, but to be somewhat realistic this number cannot be too high, since the terminals are able to communicate freely, without being jammed, as long as the jammer is listening. In addition, the clock drift might also become a problem, if the jammer listens for too long.

The first simulation (see Figure 3) shows the performance of the proposed jammer, compared to an omnidirectional jammer and a genie jammer. The genie jammer knows the true frame timing as well as the true channel to terminal A. These two benchmark jammers are two extremes, one applies perfect beamforming, the other does not beamform at all. The simulation is run with the jammer having $M = 100$ antennas, at relative distance $d_r = 3$, and listening to $K = 50$ coherence blocks. The simulations are shown for jammer power advantage ρ_J/ρ_p from -20 dB to 20 dB in Figure 3.

The performance of the proposed jammer is very close to the genie jammer, less than one dB difference. Comparing the proposed jammer with the omnidirectional jammer, it can be seen that the proposed jammer can do the same damage to the primary link as the omnidirectional jammer with close to 18 dB less output power. Another thing to note is that when the jammer and the primary link have the same output power, the damage that the omnidirectional jammer causes is minimal, the capacity of the primary link only drops about 1%. Compare this to the proposed jammer, where the maximum rate of the primary link drops to less than 30% of its nominal capacity.

Figure 4 shows how the primary rate is affected when the jammer is placed at different relative distances from terminal A. Here, the jammer has no power advantage over the primary link, i.e. $\rho_J = \rho_p$.

A few observations can be made from looking at the Figure 4. First, when the jammer is close to the primary users, the jammer performance is close to perfect. Second, for large relative distances, the proposed jammer performs no better

Fig. 3. Rate of the primary link as a function of jammer power advantage ρ_J/ρ_p . The jammer's parameters are: $M = 100$ antennas, $K = 50$ blocks, and relative distance $d_r = 3$.

Fig. 4. Rate of the primary link as a function of relative distance d_r . The jammer's parameters are: $M = 100$ antennas, $K = 50$ blocks, and jammer power advantage $\rho_J/\rho_p = 0$ dB.

than the omnidirectional jammer. The distance between the jammer and terminal A obviously degrades the performance of the jammer due to the increased attenuation of the jammed signal, but this alone does not explain the rapid deterioration of the proposed jammer. The effect of increased attenuation of the jamming signal on its own can be seen on the performance of the genie jammer. The distance between terminal A and the jammer affects the received signal power *at the jammer*. The further away the jammer is, the lower the SNR at the jammer, and at some point, the received signal will mostly consist of noise. This means that the frame timing will be difficult to estimate, and as a consequence, the channel estimates will be poor. If the jammer is very far away, the dominating eigenvector of the sample covariance matrix will be a random vector, associated with the noise w .

How the number of antennas at the jammer affects the

performance can be seen in Figure 5. The beamforming ability improves for each antenna that is added to the jammer. Ideally, the beamformed noise will scale linearly with the number of antennas, M , as the transmitted signal from the jammer experiences an array gain equal to M .

Fig. 5. Rate of the primary link as a function of number of antennas M . The jammer's parameters are: relative distance $d_r = 3$, $K = 50$ blocks, and jammer power advantage $\rho_J/\rho_P = 0$ dB.

As stated before, an incorrect estimate of T_0 can greatly degrade the jamming performance. There are two main factors that contribute to how well the frame timing can be estimated, the first being the SNR observed at the jammer, and the second how many coherence blocks the jammer listens. Figure 6 shows how the relative distance affects the accuracy of the T_0 estimate. Here, the jammer has 100 antennas and the jammer listens to 50 coherence blocks. It can be seen that as long as the SNR at the jammer is good enough, the jammer estimates the frame timing quite well for this scenario. However, just as one can suspect from looking at Figure 4 there is a threshold when the SNR is just too low to estimate the frame timing accurately. The distribution of the errors can be seen going from a very peaky normal distribution, to a uniform distribution from $-\tau_C/4$ to $\tau_C/4$. Similar results can be seen when comparing the accuracy of the frame timing when listening to different number of coherence blocks. The distribution is close to normal when few blocks are used, but gets more peaky as the number of blocks increases. To be able to get this performance, the jammer needs to be close enough to the terminal to not have low SNR.

V. CONCLUSION

For the proposed jammer to be able to disrupt communication more efficiently than an omnidirectional jammer, estimation of the frame timing is crucial. A poorly estimated frame timing deteriorates the jamming performance substantially. There is a threshold, most notably in the relative distance after which the frame timing estimate proposed is not accurate. If certain conditions are met, the jammer can successfully

Fig. 6. Estimation errors ($T_0 - \hat{T}_0$) for the frame timing for different relative distances. The vertical axis shows the frequency of the estimation errors (divided in bins of size 5, symmetric around 0).

estimate the channel blindly, without any assumption of the structure of the channel. Future work will include extending the jammer to a multi-user setup and also how to handle wideband systems and frequency hopping.

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