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Technical Report

RFID Performance Tag Analysis

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Executive Summary

This report describes efforts to measure performance of item-level EPC-based passive UHF RFID tags on cell phones. The intended application is to use RFID tags to keep unauthorized cell phones from restricted areas. Our analysis shows that it *can* be done, but it is not a "silver bullet" solution. There are issues that one needs to be aware of. However, we have identified a tag and placement on a number of phones that, with the proper portal configuration, should give good performance. This report describes a number of experiments aimed at evaluating the performance of item-level (small) UHF RFID tags and identifying any potential problems or issues.

We have made the following observations and conclusions:

- We were able to obtain 4 tags: Alien ALL-9334, Avery AD-010, Rafsec 3000518, and Symbol I1030. Availability ranged from easy-to-get (Rafsec) to still-waiting (Symbol).

- All the tags are linearly polarized, and the circularly-polarized ThingMagic antennas had small but significant amounts of cross-polarization. Circular polarization is used to eliminate mismatch, but the cross-polarization introduces a polarization component. We found that the small amounts of cross-polarization can have a substantial impact on performance.

- For large (case-level) UHF RFID tags, the system is strongly forward-link limited. For these item-level tags, the system is balanced. That means small degradations in either the forward or reverse link will have an impact on performance, and a degradation in both will have a multiplicative affect.

- Quality of the Alien, Avery, and Symbol were typical for UHF RFID tags: around 85% yield and moderate variance in performance. The Symbol tag showed excellent (low) variance and high (100%) yield. This means that tags must be screened before deployment and adequate performance, and may need to be periodically checked to ensure continued operation.

- We found that in ideal situations (i.e., not on a cell phone), all but the Avery tag will give adequate performance for the portal application.

- We found that the Rafsec tag was the only tag that we could consistently find good placement on cell phones.

- All tags showed a dipole radiation pattern, which has two significant "blind spots." All but the Rafsec showed interesting frequency-dependent behavior, but not substantial enough to be of concern to this application.

- We found that a Rafsec on some of the Nokia cell phones actually performed better than in free space, giving good performance past 5 feet in many orientations. We also observed a fundamental change (different, not worse) in the radiation pattern of the tag when placed on the cell phone.

- In general, item-level tags are not robust when placed near water or metal. Thus, if the tag is placed against the human body, even if there is a small separation, performance will be so degraded as to be unusable. It will be quite easy to even accidentally defeat the portal system.

We conclude that item-level tagging of cell phones can be effective to reduce accidental entry with unauthorized cell phones if the portal system is deployed correctly. However, the operator should understand that the system has numerous limitations, and will not be able to eliminate unauthorized access. The portal must be configured and operated carefully to be effective.

RFID Tag Performance Analysis

1 Introduction

This report describes efforts to measure performance of item-level EPC-based passive UHF RFID tags on cell phones. The intended application is to use RFID tags to keep unauthorized cell phones from restricted areas. To study the effectiveness of this application, we first study the general nature of item-level RFID tags.

We began by trying to assemble as many item-level RFID tags as we could. Our preference was to get Gen 2 products. However, that proved practically impossible to get sufficient quantity, so we settled for Gen 1 products. Our initial requirement was to obtain as many tags that were no larger than 2 inches square. Obtaining tags proved much more difficult than we anticipated. One example that illustrates this difficulty is obtaining Symbol tags. We identified two Symbol tags that fit our requirements and set out to obtain the tags. Symbol directed us to one of their distributors. Since then, and for over 3 months, we have been in weekly contact (often more than once per week) trying to obtain the status of our request. Most of the time, we were not able to contact the representative, and those times that we did, we were assured that we would have something "next week." They did eventually send us tags — some Alien Squiggle and Rafsec 457 (large, case-level) tags. We still have no Symbol tags. Instead, for this report we used Symbol tags that we obtained in Fall, 2004.

Clearly, smaller tags have a small aperture, and the aperture is directly linked to performance. Small aperture antennas cannot collect energy as efficiently, and their radar cross signature (RCS) is also smaller. That size difference causes some significant differences in their fundamental behavior from from large tags. For example, we found that with large tags, the system is largely forward-link limited, meaning the performance was almost entirely limited by the amount of energy that the tag can collect. Smaller tags are almost balanced and are only weakly forward-link limited, meaning that small degradations in the forward and reverse link can cause significant changes in performance.

We begin the report in Section 2 by describing the devices used in testing: tags, phones, reader, reader antenna, and test apparatus. One thing we noticed about midway through the project is that the circular antennas we were using suffered from some small level of cross-polarization. (Some cross polarization is common for circularly-polarized patch antennas.) What we discovered was that the small amount of cross polarization had such a profound impact on performance.

Unfortunately, we found that much of our data was taken using an unmatched configuration (we define *matched* and *unmatched* configuration in Section 2). Furthermore, the fact that the system is not forward-link limited and that performance is not even monotonic with respect to distance and power setting, it is impossible to correlate the two. Instead, we tried to re-sample the data as much as possible in the matched configuration. Time limits prohibited us from completely re-sampling all the data.

To understand item-level UHF tags, and to understand whether it is possible to use them for tracking cell phones into restricted areas, we designed several experiments. We began by looking at variation in performance of tags. From past experience, we know that two seemingly identical tags can have significantly different performance, and some tags can be severely degraded or completely non-functional ("dead.") Variation in tag performance is the topic of Section 3.

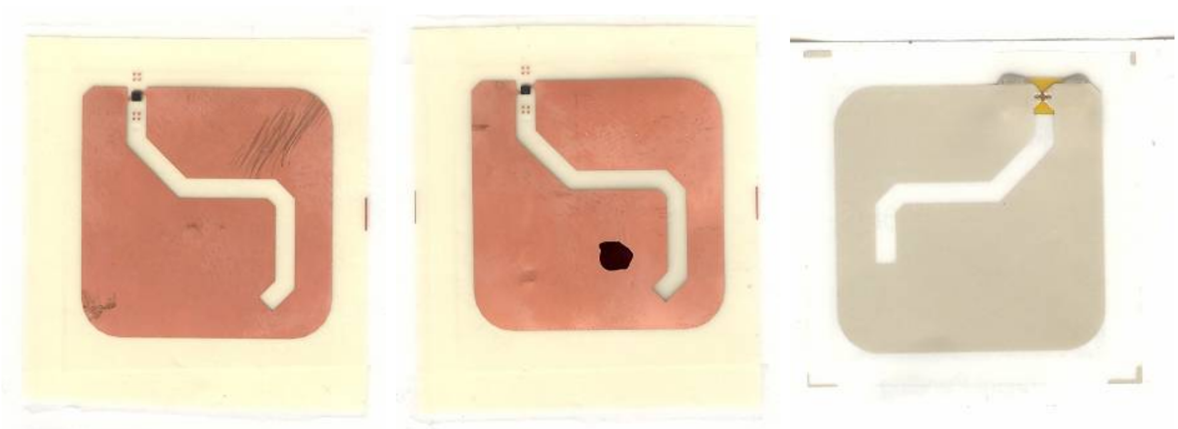
Next, in Section 4, we examine one of the most basic performance questions: how far away can a tag be read? To do that, we designed an experiment in which we placed tags in an ideal orientation and measured how they performed at various distances.

Tags are not always oriented ideally, and tag performance can change significantly with orientation and frequency. That topic is the subject of the next two sections. In Section 5, we show how the radiation pattern of the antenna changes with respect to frequency. Then in Section 6, we show how far away one can read a tag at different orientation, both in free space and the Rafsec tag mounted on cell phones. We unveil some interesting artifacts, but nothing that will substantially impact performance. What we show is that with tags on phones, the radiation pattern changes, and in some circumstances, the performance actually *improves.*

We also know that tags behave differently in the presence of dielectric and conductive materials, such as water and metal. Water is particularly interesting because the human body is mostly made up of water, and cell phones are commonly stored close to the body. Our data in Section 7 shows that tags near water (and metal) do not fair well.

Finally, we summarize our findings, important conclusions, and future work in Section 8. Our results show that the Rafsec tag placed on cell phones show adequate and even good performance for the intended application, but placing the tags near metal (e.g., keys or change) or water (e.g., human body) will severely degrade performance.

Figure 1: Alien ALL-9334



(a) (b) (c)

Figure 2: Avery Dennison item-level tags: (a) Avery Dennison AD-010 inlay, good (this is the tag we tested in this report) (b) Avery Dennison AD-010 inlay, marked bad, and (c) slightly older Avery Dennison AD-010 sample utilizing a strap and slightly different antenna.

2 Equipment Description

This section describes all the products and equipment that were used for testing this report: tags, phones, reader, reader antennas, and test apparatus.

2.1 Tags

For this project, we sought all commercially available EPC-based UHF RFID tags that were smaller than 2 by 2 inches. We were able to obtain the following RFID tags: the Alien ALL-9334 (Figure 1), the Avery Dennison AD-010 (Figure 2), the Rafsec 3000518 (Figure 3), and the Symbol I1030 (Figure 4). These represent all the tags models that we were able to obtain in a timely manner.

Our mandate was to give preference to obtain Gen 2 products. The only Gen 2 product that we received was a sample of 4 Rafsec / Impinj designs. We did not view that as sufficient quantity for testing, nor are they available in production quantity for use. Thus, we chose not to test that tag for this report.

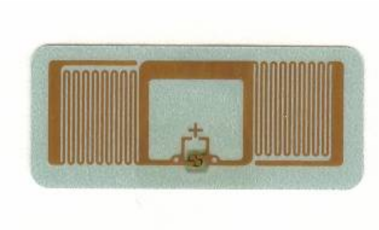


Figure 3: Rafsec 3000518

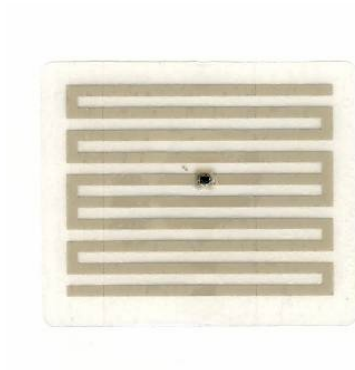


Figure 4: Symbol I1030

We received 20 samples of the Alien AL-9334. The entire tag, including antenna and small margin, measured exactly 2 inches wide by 1 7/8 inches tall. Thus, it was the largest tag that we tested. The Alien tag is a 96-bit Class 1 tag encased in a "strap." We received those fairly early in the testing process, and it is our impression that the availability of these tags are fair.

The Avery AD-010 (hereafter "Avery") tag is a Class 1, 96 bit tag. The antenna size measures exactly 1 by 1 inch, so a label would be slightly larger than that. Availability was fair: we were able to obtain tags after 6–7 weeks of trying, but we were willing to accept unconverted inlays, which may have expedited the process. All the Avery tags used a 96-bit Class 1 chip. Early on we obtained a small number of samples (two) that used the strap (similar to what Alien uses for their products, see Figure 2c). We placed an order for 200 tags (at $1.00 per tag) for unconverted inlays, i.e., they had not been converted to inlays (see Figure 2a). They arrived as a continuous role of tags with approximately half of the tags having a black dot on them (Figure 2b). The black dot apparently indicates that the tag had failed quality standards, although we found that approximately one third of those with black dots did work, although somewhat poorly. For this report, we excluded tags with black dots from testing.

Also, interesting to note that the tags that we obtained did not have straps, but rather were direct chip attach. Also, we observe that on the Avery Dennison web site `http://www.rfid.averydennison.com` that some pictures of the AD-010 are shown with straps and some are not. It may be that Avery has two versions of this product: one with straps, and one with direct chip attach.

The Rafsec tag was by far the easiest to obtain. Within two weeks of the start of the project, we received two roles of 100 tags from two different sources. The entire label measures 1.5 by 3.5 cm, or 0.59 by 1.38 inches. It was also used a Class 1 96-bit tag.

Finally, the Symbol I-1030 (Figure 4) tags that we tested were not obtained during the course of this project. Rather, they were tags that we obtained Fall 2004 for another project. The handful of samples (two or three) that we obtained from other sources seemed to match the performance of the older tags in every way. Thus, we included the tag in this report. We note that availability for both this and another Symbol item-level tag was poor. Repeated requests, often multiple requests per week, to their designated distributors were not successful. Nor were attempts to get tags directly from Symbol, or for Symbol to

(a) (b)

Figure 5: Reader equipment: (a) ThingMagic Mercury4 reader, and (b) ThingMagic high-performance circular antenna.

recommend another distributor. The I-1030 is a 64-bit Class 0 read-only tag. The entire inlay / label measures 1 3/16 by 1 7/16 (approximately 1.25 by 1.5) inches.

There are other tags that appear to be commercially available, but we were not able to obtain them for testing. One is a Symbol tag claiming measurements of 0.98 by 1.3 inches, which would have been ideal for our testing. However, after repeated requests to two distributors, in addition to Symbol, we were not able to obtain these tags. Indeed, we still have two requests for tags in with vendors, but as of the time of this writing, they have still not been satisfied.

Midway through the project we learned that Precisia has a tag that fit the requirements. (Precisia does not seem to advertise their products publicly). Initial inquiries seemed promising, but we eventually were denied access to tags. Pressing the Precisia representative, we found that they had a policy of not supplying tags to academics, supposedly because of poor past experiences. We eventually got the "OK" approximately a week before this report was due. Due to some mis-communication, we were not able to obtain the tags in time for this report.

2.2 Reader

For all experiments in this report, we used the ThingMagic Mercury4 (see Figure 5a). The Mercury4 ran the operating system Linux rfid 2.4.22-uc0 #203, RadiOS version 2.0.47 (2004-08-03T17:58:51-400). We used the "high performance" UHF circularly polarized antennas (Figure 5b).

2.3 Reader Antenna

For this experiment, we use the ThingMagic circularly polarized "high performance" antenna (see Figure 5b). Tags are largely based on a dipole designs, which are inherently linearly polarized. Two linear antennas can communicate well if they mutually aligned, e.g., both horizontal or both vertical. However, if one is vertical and the other is horizontal, the antennas have a polarization mismatch and will not be able to communicate. For this reason, RFID readers often employ circularly-polarized antennas which will communicate with a linearly-polarized antenna (tag) equally well regardless of the alignment. One can think of circularly-polarized antennas as roughly equivalent to an antenna half vertically polarized and half horizontally polarized, so power transfer operates at 50% efficiency but is alignment-independent.

We note that the ThingMagic antenna is not exactly circularly polarized, and indeed has a significant amount of cross-polarization. One can think of this as being slightly elliptical, or favoring one alignment over another (e.g., favoring horizontal over vertical). Even though the cross polarization is relatively small, we found that the results on performance can be quite substantial.

To illustrate, we present two sets of tag performance data. The details of the experimental procedures are discussed in following sections, but the data is presented here to illustrate the performance implications of the cross polarization.

2.3.1 Configuration vs. Variance

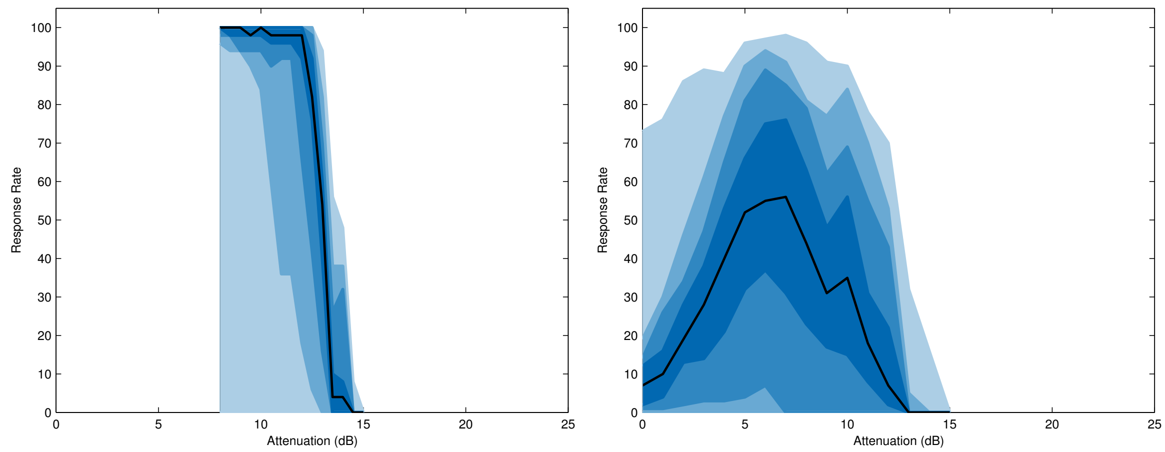
First, we studied how the "configuration" affected the measurement of variance of tag performance. For both configurations, the tag and reader were facing each other. The first configurations, which we call *matched*, is the condition in which the reader antenna was oriented horizontally and the tag was oriented horizontally. The second, which we call *unmatched*, is the condition in which the reader antenna was oriented horizontally and the tag was oriented vertically, or the reader was oriented vertically and the tag oriented horizontally.

The variance experiment is described in detail in Section 3. Briefly, we set the tag 12 inches from the transmit side of the antenna, varied the power setting of the reader from full power (30 dBm) to -25 dB of full power (5 dBm). We recorded the response rate of 50 Rafsec tags, and repeated the experiment for both matched and unmatched configurations.

The results of the two orientations are given in Figures 6. Note that in Figure 6a, the highest power setting we tested was -8 dB of full power. One can see that there is a considerable amount of variance in performance between the matched and unmatched configurations, although the distance in which most tags become completely unreadable is about the same. This result is significantly different from what we have observed from larger tags. What this data suggests is that there is a considerable amount of cross polarization of the reader antenna.

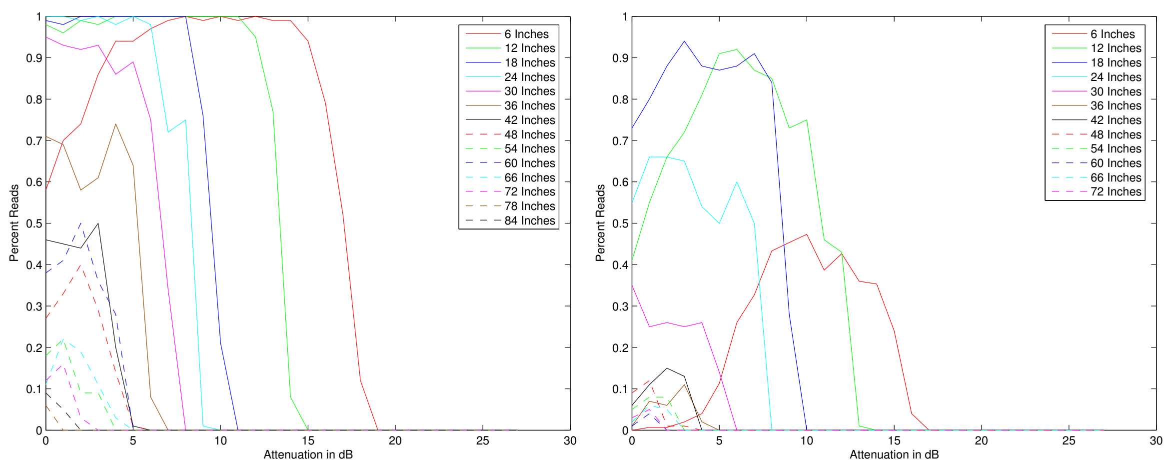
2.3.2 Configuration vs. Performance at Distance

Next, we measured the performance of the tags in an ideal orientation at various distances. The procedure is explained in Section 4. Here, we varied the distance and the power level



(a) (b)

Figure 6: Rafsec variance test: (a) matched orientation, and (b) unmatched orientation.



(a) (b)

Figure 7: Rafsec tag response rate vs. distance and power: (a) matched orientation, and (b) unmatched orientation.

of the reader and observed the response rate for the matched (Figure 7a) and unmatched (Figure 7b) conditions.

We note several important differences between the two plots. First, in general, the tag reaches the 0% response rate at a lower power level in the unmatched condition. That feature is likely attributed mostly to the degradation in the forward link. Second, for the unmatched condition, the response rate never reaches 100%. That is most likely due to degradations in the reverse link, so that the reader does not read the tag correctly even though the tag is (likely) responding.

Third, we note that in the unmatched condition, at close distances, and high power levels, increasing the power actually *decreases* the response rate. That is an interesting and counter-intuitive result. In general, higher power levels should increase the power to the tag, increase the signal being reflected from the tag, and hence increase the reflected signal being sensed

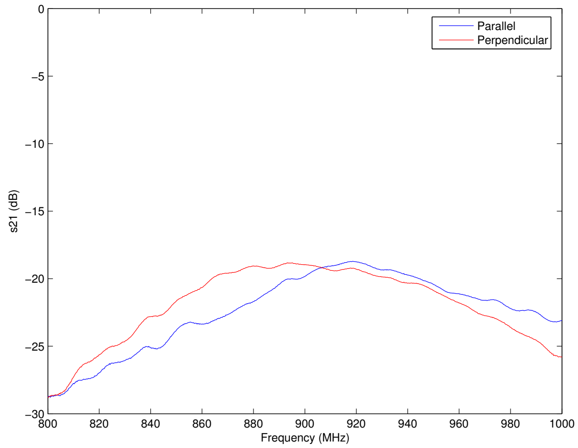


Figure 8: S_{21} of antennas, parallel and perpendicular.

by the reader. We speculate that it is also increasing the "noise" to the receiver (carrier that is being reflected by other objects), and the Mercury4 reader is not able to isolate the reflected signal from other reflections. More advanced algorithms in future versions of the radio may be better able to compensate. However, for the setup we present here, it is an important result, and shows that increased power may sometimes improve and sometimes degrade performance.

2.3.3 Direct Measure of Cross Polarization

To verify the level of cross polarization, we performed a quick measure of the cross polarization. We set up a small antenna range inside, *not* in an anechoic chamber or antenna range. Thus, the accuracy of the results should not be overly trusted, but at least this gives us a direct measure of the cross polarization. We took measures of the S_{21} using a network analyzer. Briefly, the S_{21} is a measure of what fraction of power that is sent to the transmit antenna is received by the receiving antenna. The results are given in Figure 8. The blue line was measured when the two antennas were parallel, and red when one was oriented 90 degrees from the other. If the antennas were perfectly circularly polarized, there would be no difference between the two lines. If they were linearly polarized, then the red line would be zero. The difference between the two lines is an indication of the level of cross polarization of the antennas.

What we see from Figure 8 is that the two lines intersect at about 906.5 MHz, and it is at that frequency that the antenna is ideally circularly polarized. Above that point, we see a minor difference. It appears that small manufacturing defects are introducing approximately 2 dB cross polarization or less from 900 to about 960, which in our experience for commercial-grade antennas, is fairly good.

Data from the previous sections suggest that the antennas may have large amounts of cross polarization, but direct measurement indicates relatively small cross polarization. When combining these two pieces of data, it suggests that the circular polarization of the antenna is not that significant of an issue, but rather that the reader-tag communication system is very sensitive to small perturbations in both the forward *and* reverse channel.

Previously, for larger tags, we have found that the reader-tag system is strongly forward-link limited. This new data suggests that for item-level tags, the reader-tag system is balanced, and that a small degradation in both forward and reverse channel (caused by polarization mismatches) will cause a significant degradation in performance.

2.3.4 Implications

This information suggests that having polarization diversity in the portal setup may gain significant advantages over a circular antenna. For example, having two sets of linearly polarized antennas, both horizontally and vertically, may yield even more performance than we we observed in this study. Designing and testing a reader portal configuration lies outside the scope of this work.

Unfortunately, we did not discover that the matched or unmatched configuration had such a profound impact on performance until we had taken nearly all the data we intended to present in this report. As time permitted, we have re-ran experiments and took data in the matched configuration. Unfortunately, a significant amount of data remains that was taken in the unmatched configuration. We clearly label all data taken in the unmatched configuration in this report.

2.4 Phones

We were able to obtain a handful of phones for testing. We were able to find some combination of tags and phones that worked. The phones that we were able to tag with the Rafsec tag were: Nokia 3360, Nokia 8265, Nokia 3560, Nokia 63401, Nokia 3558i, and Sony Ericcson T610. Phones we were not able to find any working tag were: Motorola "flip phone," Nokia 5165, and Samsung VGA 1000. These phones are pictured, together with tag placement, in Figures 9–17. For those phones which we were able to find suitable tag placement, we illustrate here how we placed the tag on the back of the phone.

(a) (b)

Figure 9: Motorola flip phone: (a) front, and (b) back.

(a) (b)

Figure 10: Nokia 3360: (a) front, and (b) back.

(a) (b)

Figure 11: Nokia 3560 : (a) front, and (b) back.

(a) (b)

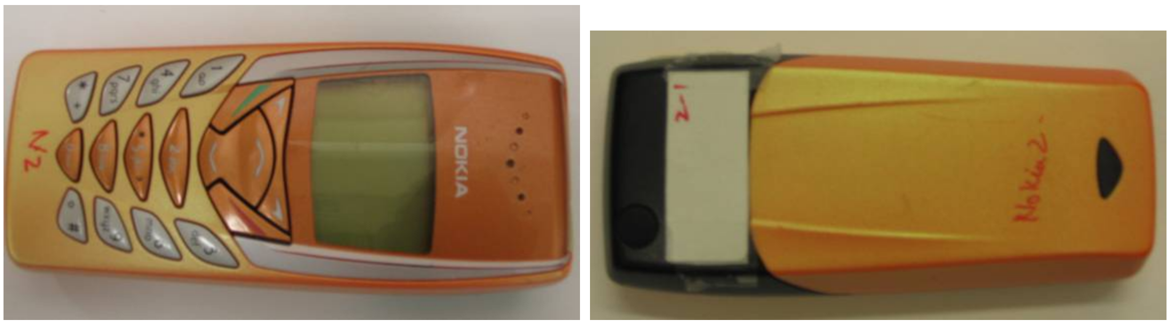
Figure 12: Nokia 3558i: (a) front, and (b) back.

(a) (b)

Figure 13: Nokia 5165: (a) front, and (b) back.

(a) (b)

Figure 14: Nokia 63401: (a) front, and (b) back.



(a) (b)

Figure 15: Nokia 8265: (a) front, and (b) back.

(a) (b)

Figure 16: Samsung VGA 1000 flip phone: (a) front, and (b) back.

(a) (b)

Figure 17: Sony Ericcson T610: (a) front, and (b) back.

2.5 Other Equipment

For this project, we developed a new capability for automatically testing radiation patterns. We obtained an 8-inch rotator table connected to a stepper motor. The stepper motor was connected to the table through a 1:360 gear ratio, and the stepper motor is a half-stepping motor. Thus, we were able to obtain 1/400 degree precision in rotation. The stepper motor was under a control of a PC that was programmed via a serial cable. Thus, we were able to completely automate data collection for one tag at one distance. For example, all the data collected in Figure 29 was taken without any human intervention.

To separate the tag or phone from the table, we built a stack of extruded polystyrene layers approximately two feet tall. Extruded polystyrene ("Styrofoam") is essentially invisible to UHF frequencies. The antenna would often be placed on a table, and we used foam blocks to adjust the height of the tag.

In the future, we plan to invest in additional automation so that we can adjust distance and orientation with stepper motor precision and entirely under software control.

3 Variance of Tag Performance

The purpose of this test is to determine how much variance in performance there is between tags of the same model. For the remainder of this section, we consider performance to be analogous to how far away a tag can be read. In this section, we do not measure distance (we do in some of the following sections). Instead, we adjust the power level of the tag. This is done because it can be automated easily, and allows us to take more data. Also, variance found in this study will be directly correlated to performance over distance, although we found the translation difficult for item-level tags.

If a model has low variance, it is likely that any two tags will have the same performance. If the variance is high for a model, then two tags are likely to have different performances.

3.1 The Test

The requirement for this experiment is a reliable setup for which one can observe the maximum amount of possible variance between tags. We chose to place the tag 12 inches from the transmit side of the antenna. (A discussion of why we chose that setup is given in Section 5.1.) Then we varied the power setting of the reader and measured the response rate of some number of different tags.

Note that the Alien, Avery, and Rafsec tags and reader were in an *unmatched* configuration (see Section 2.3); ideally, these measurements should be taken in the matched orientation. We started each tag by reading it with 100 attempts at full power. We then attenuated the power by 1 dB steps (1 dB reduction is approximately 80%, 3 dB is approximately 50%, and 10 dB is 10%). At each power setting, we performed 100 read attempts and recorded the fraction of successful reads.

The tests were not performed in an anechoic chamber, but rather in a "normal" university laboratory. For all our experiments, we configured the antenna and tag as to minimize any reflections from objects, such as walls, floor, and ceiling, but some reflections were unavoidable. For example, the reader antenna was never closer than 10 feet from a wall with direct line-of-sight.

3.2 The Data

Figures 18, 19, 20, and 21 give the test results for the Alien, Avery, Rafsec, and Symbol tag respectively. The black line in the figures represent the median tag performance. The darkest blue contains the middle 40% of performers; the next lighter shade represents the middle 70% performing tags; the next lighter shade represents the middle 87% performing tags; and all tag performances fell within the lightest shade of blue.

There are two things to look for in this result. First, better performing tags will have response rates fall to 0% at higher attenuation levels. Second, high quality tags have narrow bands, that is, the difference between best and worst tag will be small. The Symbol exemplifies a very low variance tag model, but recall that the Symbol was also tested in the matched configuration. Testing tags in the unmatched configuration tends to exaggerate variance, as shown in Figure 6. Also, look for the fraction of tags that are far down and left of the median tag; the lower performing tags may need to be screened.

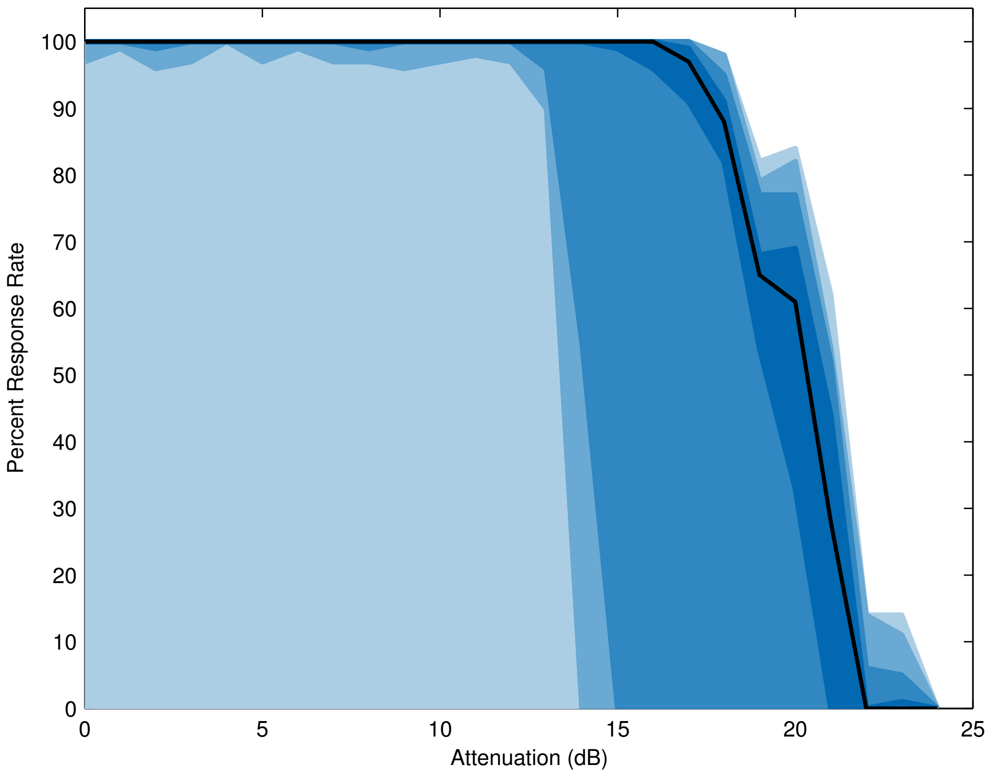


Figure 18: Variance of Alien ALL-9334, *unmatched configuration.*

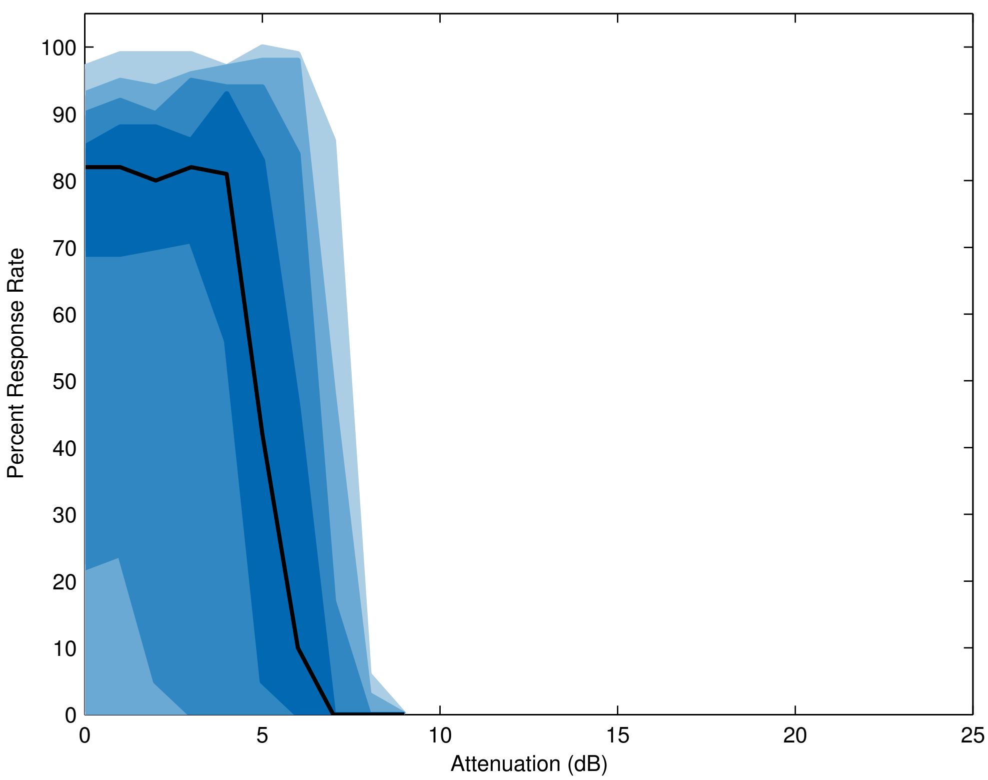


Figure 19: Variance of Avery AD-010, *unmatched configuration.*

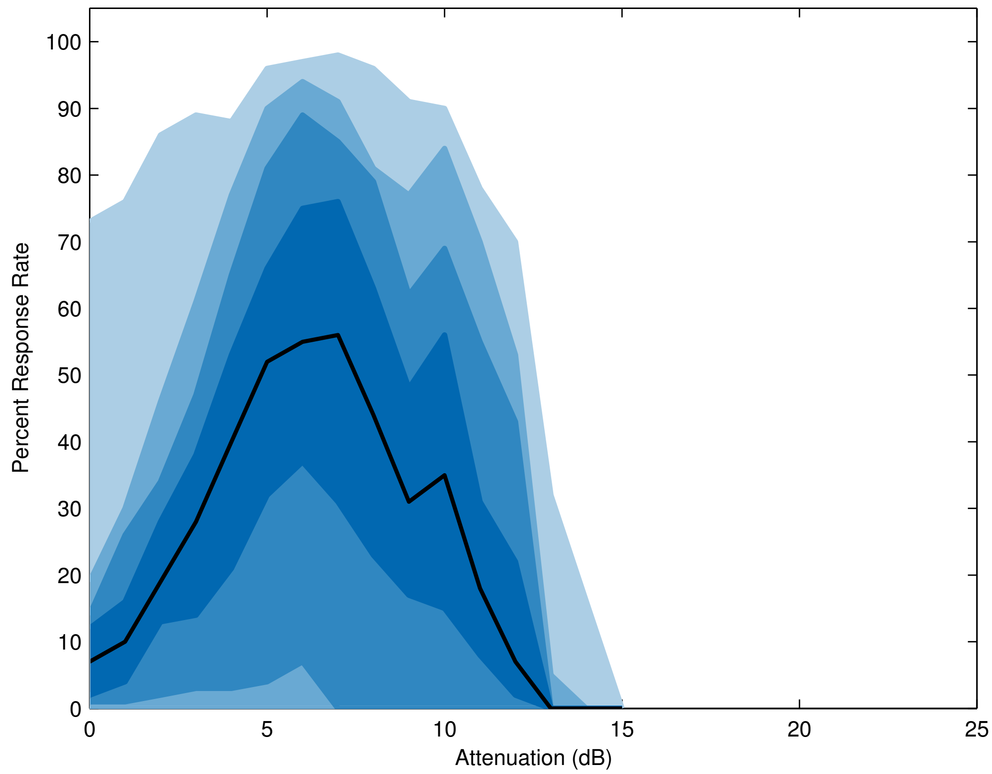


Figure 20: Variance of Rafsec 3000518, *unmatched configuration.*

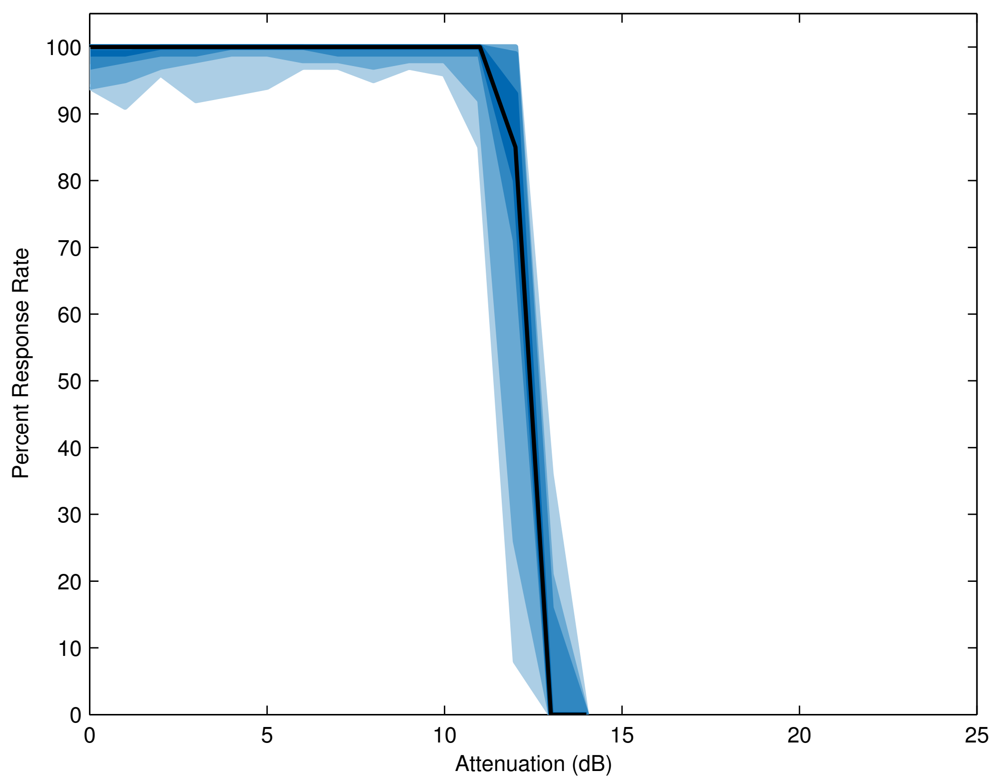


Figure 21: Variance of Symbol I-1030, *matched configuration.*

Table 1: Yield for item-level tags.

Tag	Total	Dead	Quiet	Yield
Alien	20	1	5	70%
Avery	22	2	0	91%
Rafsec	50	4	3	86%
Symbol	50	0	0	100%

Along with the variance data, we present some statistics on what we found as "quiet" and "dead" tags. First, we define a *dead* tag as one that when the reader is set to the highest power level, the tag held 12 inches from the transmit antenna of the reader, and the reader performs 100 read attempts, the reader is not able to read the tag. A *quiet* tag is one that is readable but performs 6 dB or less below the median performing tag (6 dB corresponds to approximately half the read distance). We show statistics in Table 1.

We must point out that the sample sizes from which we have drawn are relatively small, so it is difficult to attach any statistical certainty to the data. However, it does indicate that the tags are not without yield issues, both with dead and quiet tags. It is worth noting that we observed the Symbol tag has 100% yield *and* very low variance in performance. This could be due to the Symbol tag using an older, more established IC.

3.3 Analysis

The data suggests that item-level tags shows variation typical of larger tags, except the Symbol tag, which gives excellent variation and yield. We observe that the Avery tag is the worst performing tag by a significant amount. This is confirmed in other tests in this report as well. Also note that the unmatched configuration tends to exaggerate variance as opposed to matched (see Figure 6). The data also shows that yield can be a significant issue all but the Symbol tag. The Avery tag did technically show good yield, except the surprising fraction of tags that were marked as bad (26 of 50), and also keep in mind that 6 dB was the extent of the performance range for the median tag anyway, so no tag that was readable could be judged as quiet.

In terms of raw performance, the Alien tag was the best performer, significantly better than the rest. The Symbol tag seems to be better than the Rafsec, but this true only because the Symbol tag was matched and the Rafsec was unmatched. When comparing Figure 6 and Figure 21, the Rafsec tag is clearly a slightly better performer. This is also evident from the tests in Section 6. The performance of the Avery tag was so poor as to disqualify it as a viable option for tagging cell phones.

3.4 Conclusions

For the Alien, Rafsec, and Symbol tags, variation is typical, which means you can expect a range of performance from tags of the same model. The Symbol tag showed near perfect variance and yield. When deploying these item-level tags for a portal application, one must be vigilant to screen tags for dead and under-performing tags.

In the future, we will use a different set of experiments that will better measure tag performance and reader sensitivity independently.

4 Tag Performance vs. Distance

One of the fundamental questions that people have around tag performance is "how far away can one read the tag." Clearly, there are a number of factors that go into measuring that. For example, the orientation of the tag, any materials near the tag, the polarization of the reader and tag antenna, and what response rate constitutes an ability to read. In this section, we address this basic question with some simplifying assumptions, namely that the tag and reader are in optimal orientation.

4.1 The Test

For this experiment, we placed each tag some number of inches from the transmit antenna in the *unmatched* configuration (see Section 2.3). We adjusted the power setting from full power to some fraction of full power in 1 dB steps. At each power setting and distance, we performed 100 read attempts and recorded the fraction of reads.

4.2 The Data

We chose a tag from the set of tags studied in Section 3, and chose a tag that was approximately a median performing tag. The tags were tested in 6 inch intervals until the tags were unreadable, except for the Alien tag which was still readable past 8 feet. The results of this experiment for the four tags are presented in Figures 22–25.

4.3 Analysis

First, we note that the Alien tag shows excellent performance. Again, it is clearly the leader in performance for item-level tags. It is also the largest.

For the smaller tags (Avery, Rafsec, and Symbol), we observe some consistent features. As power increases, the response rate increases, up until some maximum. Then the response rate reaches a plateau, and at some power level, the response rate actually *decreases* with increased power. This is especially apparent when tags are closest to the reader antenna.

From this, we can speculate two things. First, when the tag is closest to the transmit antenna, the angle between the tag and the reader receive antenna is large, and we expect that provides significant attenuation in the reverse channel. Thus, we conjecture that the tag response does reach 100% and stays at 100%, but the response rate we observe is due to the reader not being able to detect the tag response. Apparently, at higher power levels, the reader is not able to isolate the response from the tag from the reflections of other objects in the area, or from coupling between the transmit and receive antenna. An important implication is that higher power is not always better. In some cases, higher power can actually decrease the response rate. Note that this observation is specific to the reader we used. Different readers and/or different firmware on the same reader may yield substantially different results than what we observe in this section.

Another explanation is that these tags have a maximum change in reflected power. Once a tag reaches "saturation," no more additional "signal" will be reflected from the tag. This will again explain the plateaus, and the decrease at higher power levels where the signal-to-noise ratio becomes too low. We think this explanation is unlikely to be true, but it is

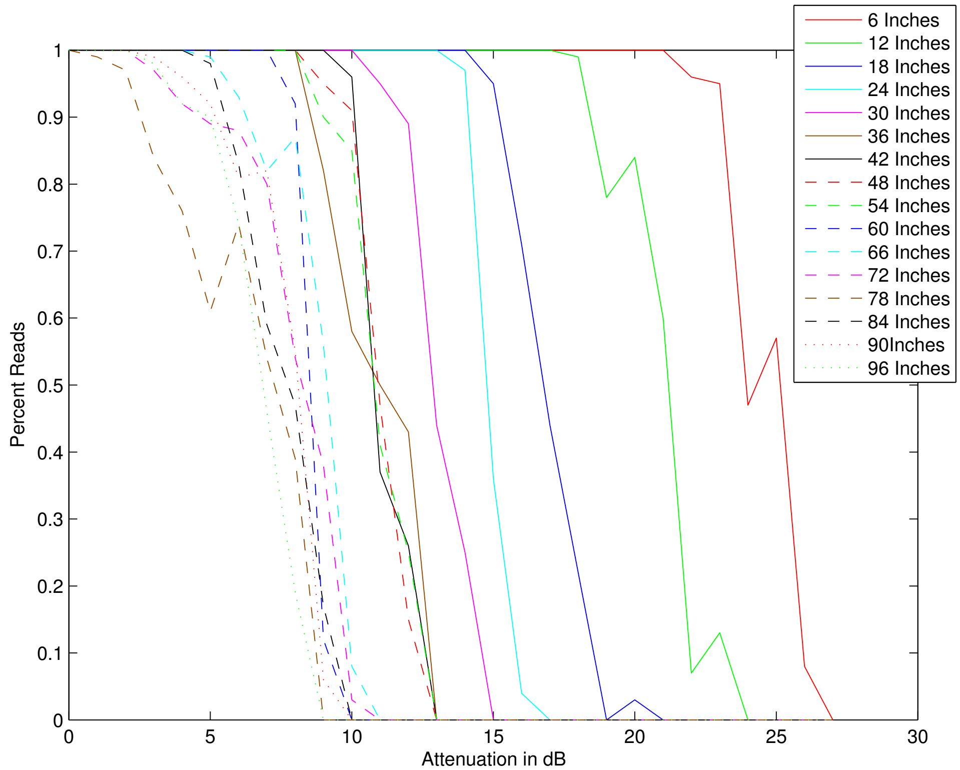


Figure 22: Alien response rate vs. distance, *unmatched*.

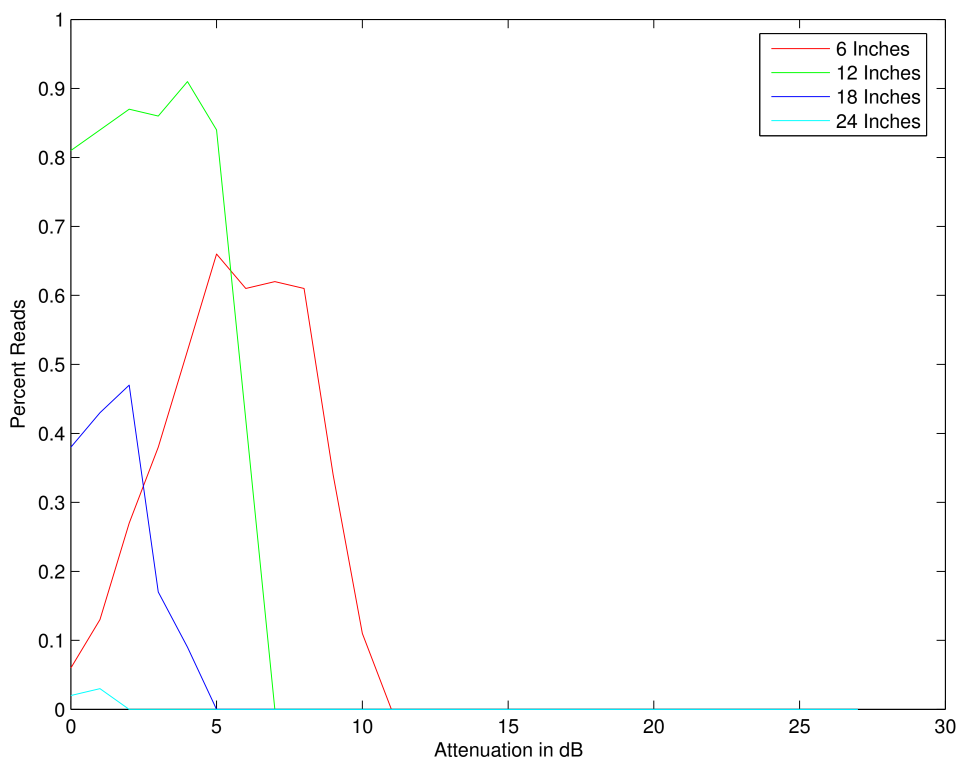


Figure 23: Avery response rate vs. distance, *unmatched*.

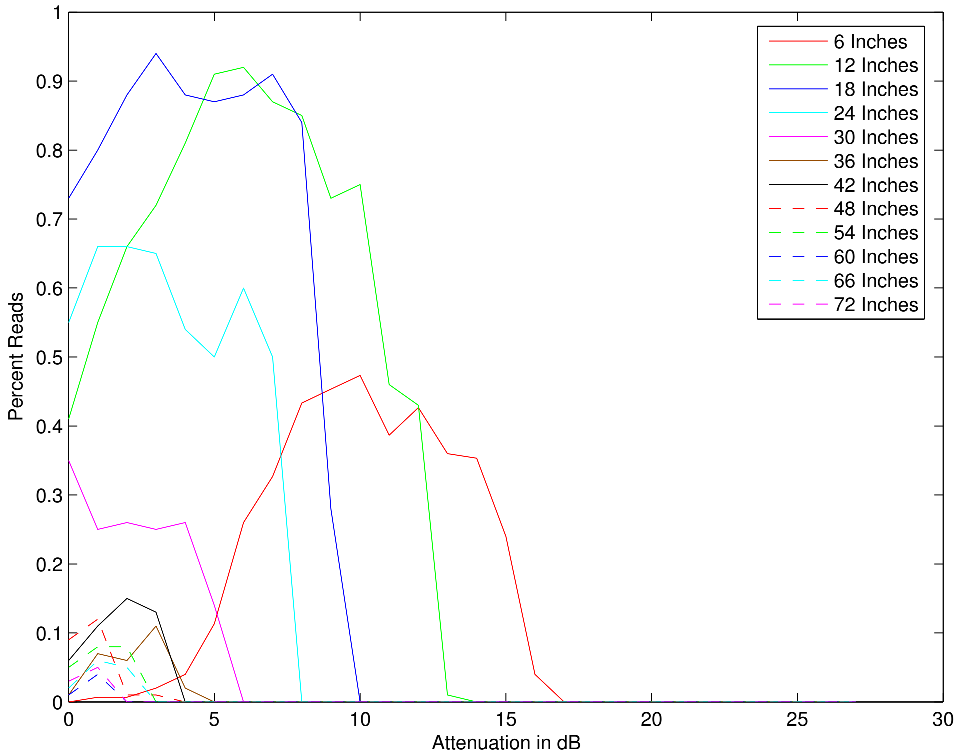


Figure 24: Rafsec response rate vs. distance, *unmatched*.

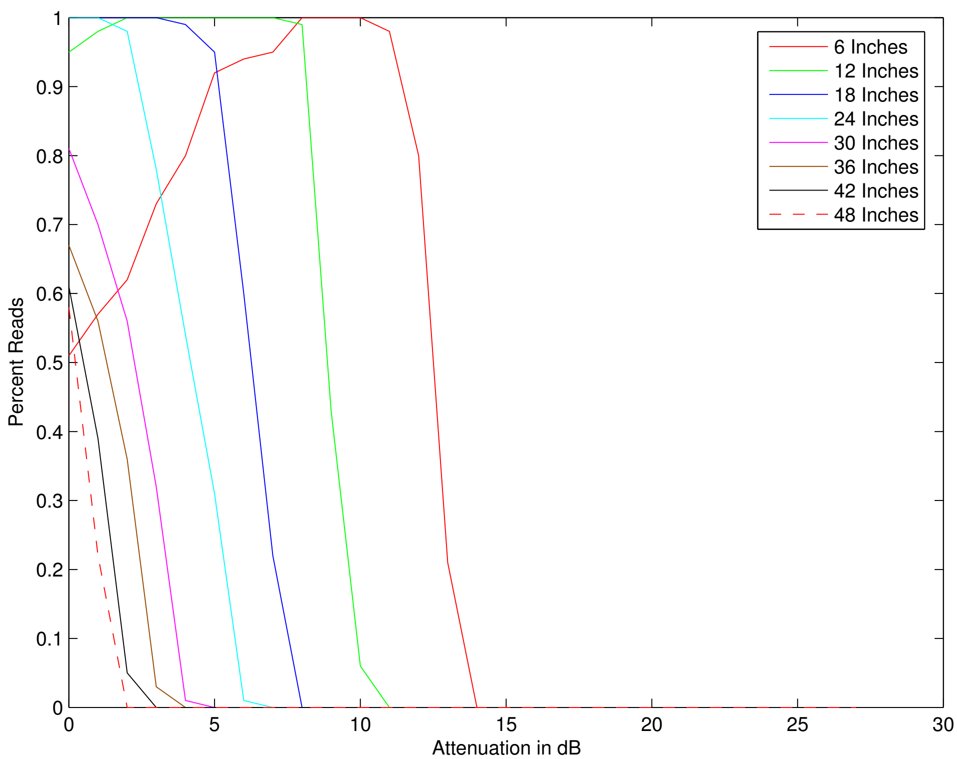


Figure 25: Symbol response rate vs. distance, *unmatched*.

impossible to determine without direct analog measurements.

Finally, we note the implications of the measurements being taken in the unmatched configuration, as illustrated by Figure 7.

4.4 Conclusions

To summarize the important findings, we find that the Alien median tag is clearly the best performer, the Rafsec and Symbol are middle performers with the Rafsec slightly better, and the Avery tag performs poorly.

We performed all tests with the tags in an unmatched configuration. Given the results, we conclude that the reader-tag system is weakly forward-link limited. System performance degrades significantly if both the forward and reverse links are attenuated even slightly. In these situations, adding more transmission power might be helpful, might do nothing, and might be harmful, depending on the particular scenario.

Some low level of performance is still achieved with the Rafsec tags out to 3 feet, which should be sufficient for a portal. However, this outlines the importance of making sure the portal is using high-quality antennas and readers. Section 6 shows good performance out to 4 and sometimes 5 feet with the Rafsec tag in a matched configuration.

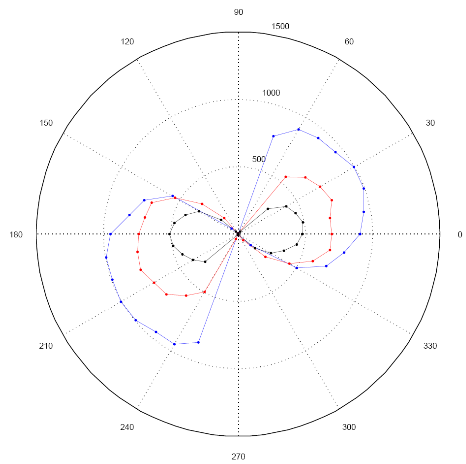


Figure 26: Minimum power level vs. orientation for three tag placements.

5 Frequency-Dependent Radiation Patterns

In this section, we focus on looking at the frequency-dependent characteristics of the item-level tags. For example, do the radiation patterns change substantially over the 902–928 MHz frequency spectrum? Does performance change substantially? (We measured behavior at 953 MHz, but did not include it in this report for brevity and because it is likely outside the interest of audiences in North America.) Since we are primarily interested in patterns and differences over frequency, we used a test procedure that was amenable to taking large amounts of data. More than one million read attempts were performed to assemble the data in this section.

5.1 The Test

We chose a typical (median-performing) tag from each model. The test configuration we used was to set the tag centered 12 inches in front of the transmit antenna. We chose a 12 inch separation because it's far enough to be in, or close to in, the far field of the reader antenna, and it seemed to be the best distance for maximizing a chance for reading a poor-performing tag.

We placed the tag in the center of the transmit antenna because, again, that was the placement that gave maximum performance. We determined this placement using a simple experiment we tested the tag performance in three different locations: 12 inches in front of the receive antenna, centered between transmit and receive antenna, and in front of the transmit antenna. For this experiment, we used the Rafsec tag.

Figure 26 shows the results of the experiment. The blue line of Figure 26 represents the radiation pattern observed with the tag centered in front of the transmit side of the antenna, the red is centered between the transmit and receive, and the black is centered in front of the receive antenna. We find it interesting that when the tag is in front of the receive antenna that it exhibits the expected figure 8 pattern, but when moved closer to the transmit antenna, it performs more favorably when the tag is facing slightly towards the receive antenna. This is a clear indication that the system is only weakly forward-link

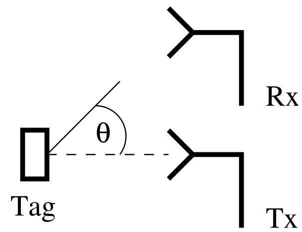


Figure 27: Setup description and angle definition.

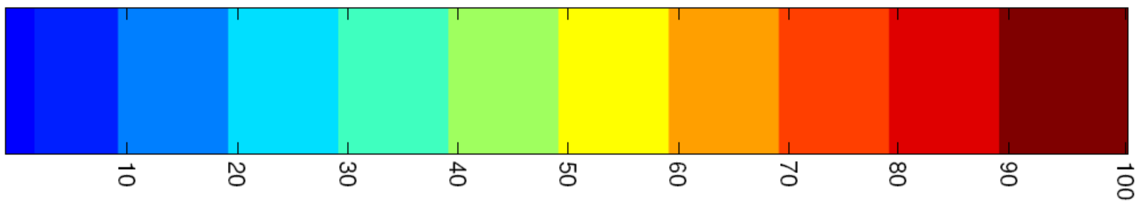


Figure 28: Color corresponding to response rate for radiation pattern plots.

limited, as the tag response rate is clearly symmetric along the horizontal axis, but the reader does not perceive the response as well when the tag is facing away from the reader.

As an aside, we performed a similar experiment with a large, case-level tag, and the results were the opposite. (We omit the results for brevity.) The tag performance for case-level tags was symmetric when centered above the transmit antenna, and when centered above the receive antenna, would respond better when the tag was facing the transmit antenna. That result is another confirmation that there is a fundamental difference between the channel capacity for large and small UHF RFID tags.

For the data presented in this section, we placed the tag 12 inches in front of the transmit antenna, and varied both the orientation of the tag (by 3 degree intervals) and the power setting of the reader (by 1 dB steps). A graphical depiction of the setup is given in Figure 27. Zero degrees corresponds to the tag parallel to the reader antenna, and small positive angles orient the tag towards the receiver antenna. At each setting, we performed 100 read attempts and recorded the number of reads. Unfortunately, some of the data in this section was taken with the tag in the matched configuration, and other data in the unmatched configuration. We clearly mark each case.

5.2 The Data

This section shows the performance of the item-level tags in free space. We vary the angle of the tag and power level of the reader, and plot response rate using a color. Warmer colors are used to represent high response rates, and cooler colors low response rate. Figure 28 shows the color to response rate translation. (Note that we performed similar frequency/orientation radiation patterns with tags on the phones, but the data does not reveal any new information, so it is omitted.)

5.3 Analysis

The most important result is that the frequency-dependence is mild and should not affect overall performance, especially with fast frequency-hopping readers.

There are numerous, fine features that we don't have an explanation for at this time. However, we note some of the interesting features. First, the Alien tag in the E plane (Figure 29) shows the familiar figure 8 pattern. We note that at 918 and 923 MHz that one or two sharp nulls appear, but disappear at 928 MHz. The null is small but distinct. The performance in the H-plane (Figure 30) has a remarkable feature at 902 MHz. Unlike the E-plane, the data goes to zero too sharply; it is likely that this is an error in the data taking process.

The Avery tag shows an unusual radiation pattern that also changes significantly over frequency. The E-plane (Figure 31) shows a distinct and sharp null in one direction. It also shows that performance is much better at 928 than at 902. The H-plane data (Figure 32) shows a similar null and similar better performance at higher frequencies. We speculate that the tag may be tuned for higher frequencies in anticipation of being placed on a low dielectric material.

The Rafsec E- and H-planes (Figures 33 and 34)are unremarkable. The tag behaves as a dipole, has no measurable nulls, and does not have a strong frequency dependence between 902 and 928 MHz. (The Rafsec performance goes to nearly zero at 953 MHz, but that is only interesting in some Asian markets.)

The Symbol radiation pattern in the E-plane (Figure 35) also shows the dipole-like behavior, except that the side lobes are narrower than they should be. (Conversely, the nulls are wider than they should be.) It does seem to have some frequency dependence. The H-plane data (Figure 36) shows the expected circular performance, except that at 907 and 912 MHz (and to a lesser extent at 902 MHz), we see a significant degradation in performance at high power levels. This has been verified with additional experiments.

5.4 Conclusions

In this section, we present data that shows that some tags have unusual frequency-dependent characteristics, including changing the radiation pattern and the occasional presence of frequency-dependent nulls. All the tags exhibit dipole-like radiation patterns, which consists of two approximately 60 degree nulls in the E-plane and circular radiation patterns in the H-plane. The Rafsec tag seems to exhibit ideal dipole-like behavior, while the other three tags have some features that are less than ideal. None of the features are large enough to cause significant concerns in performance.

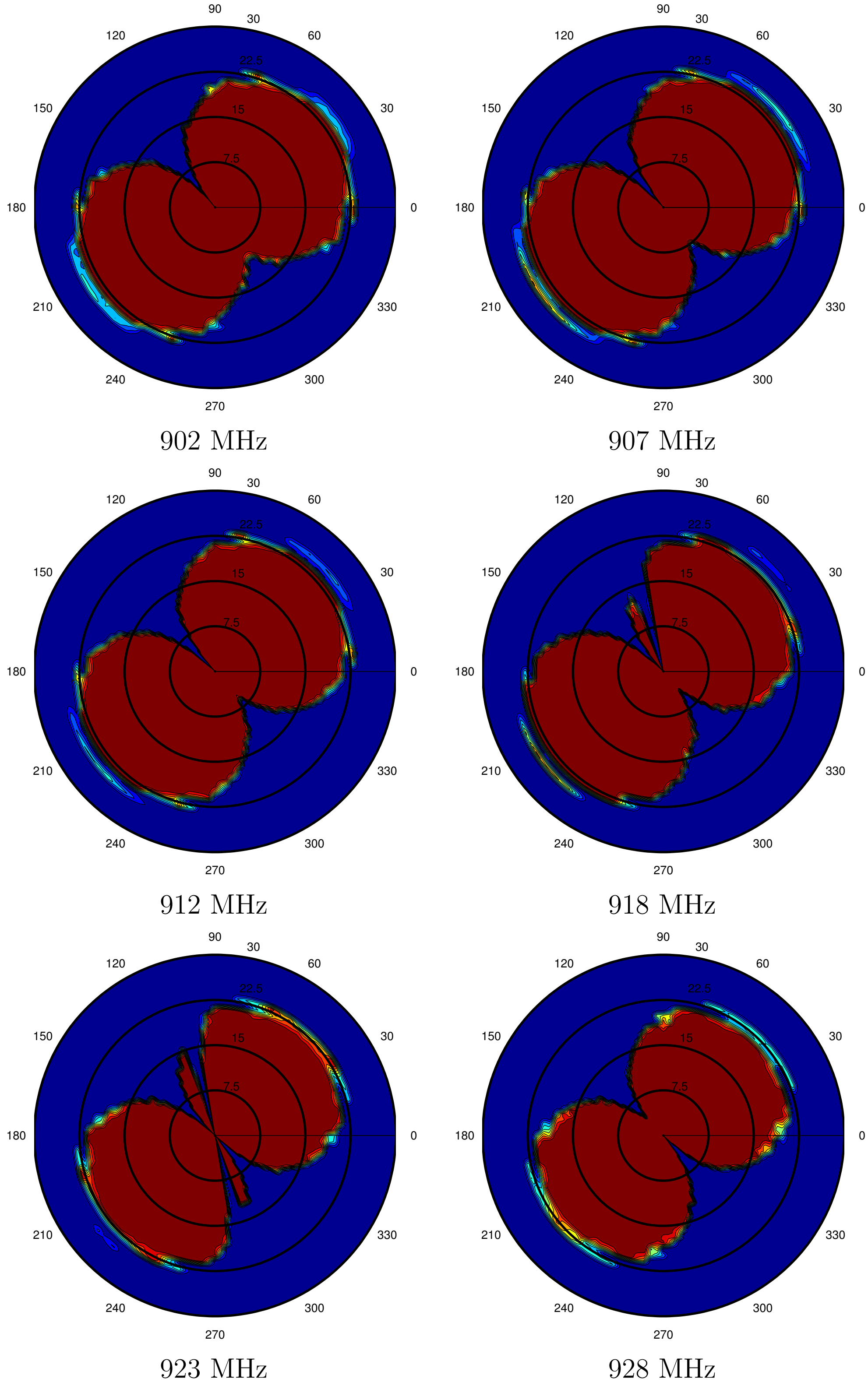


Figure 29: Radiation pattern of Alien tag in E-plane, *unmatched configuration*.

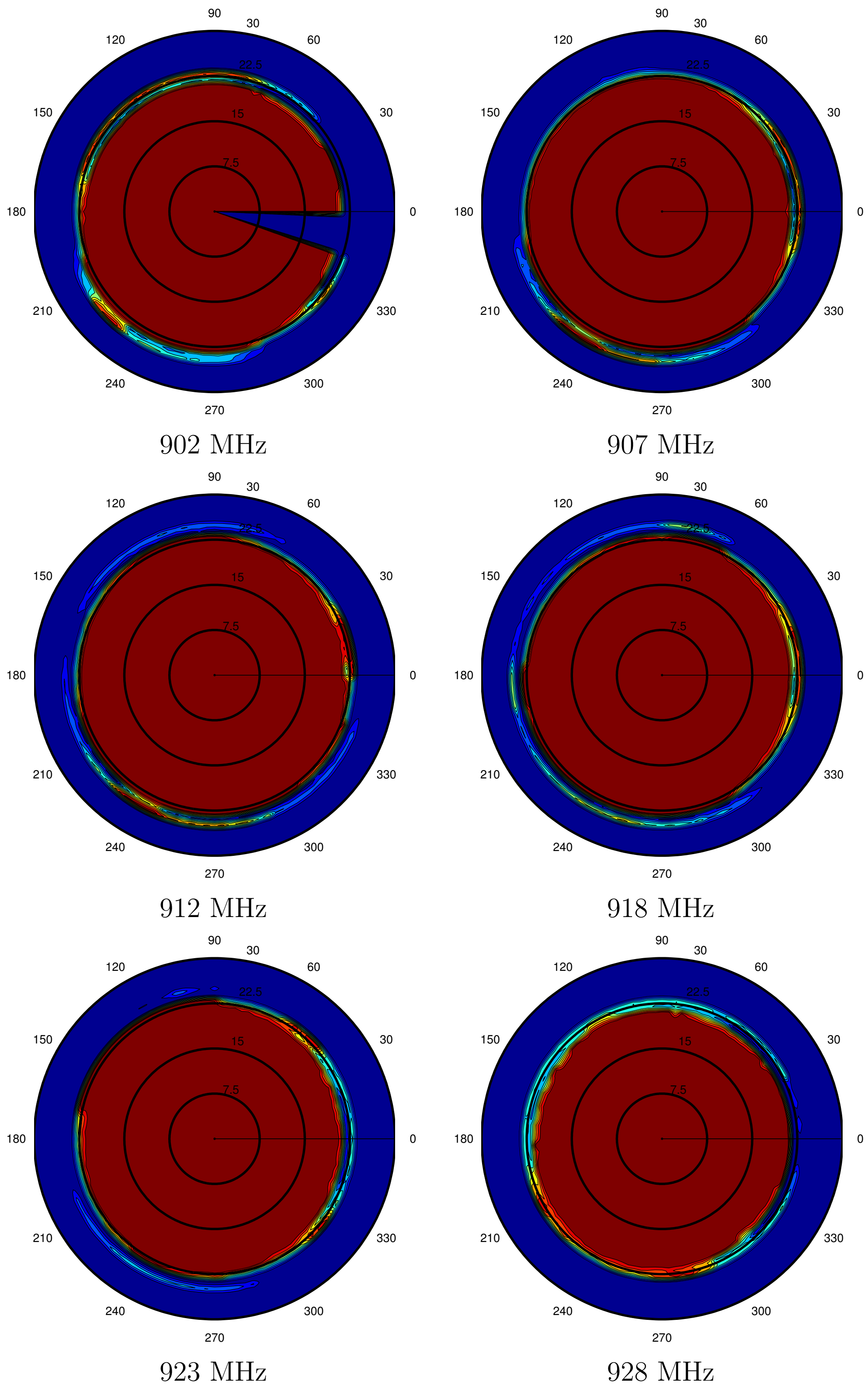


Figure 30: Radiation pattern of Alien tag in H-plane, *matched configuration*.

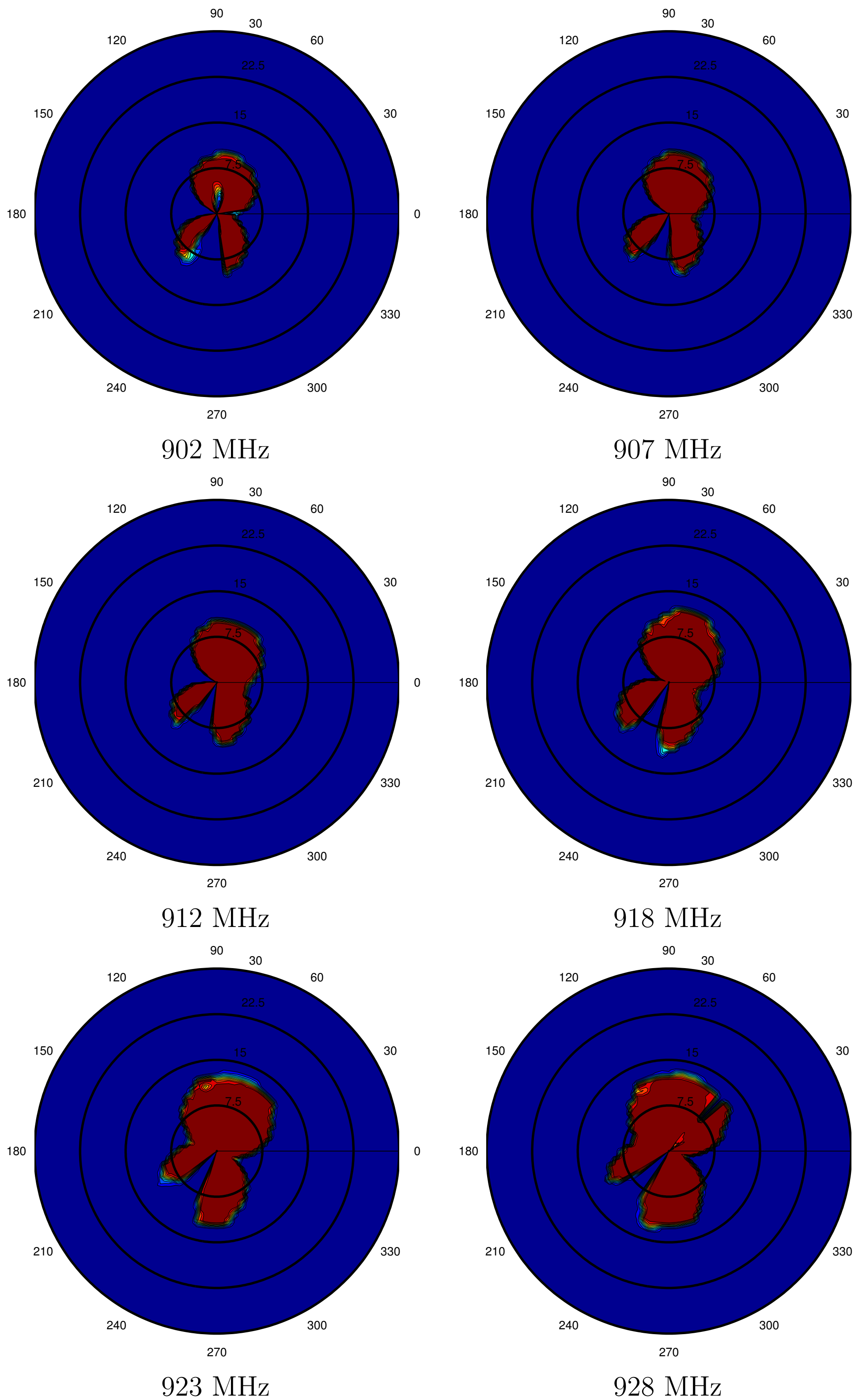


Figure 31: Radiation pattern of Avery tag in E-plane, *unmatched configuration*.

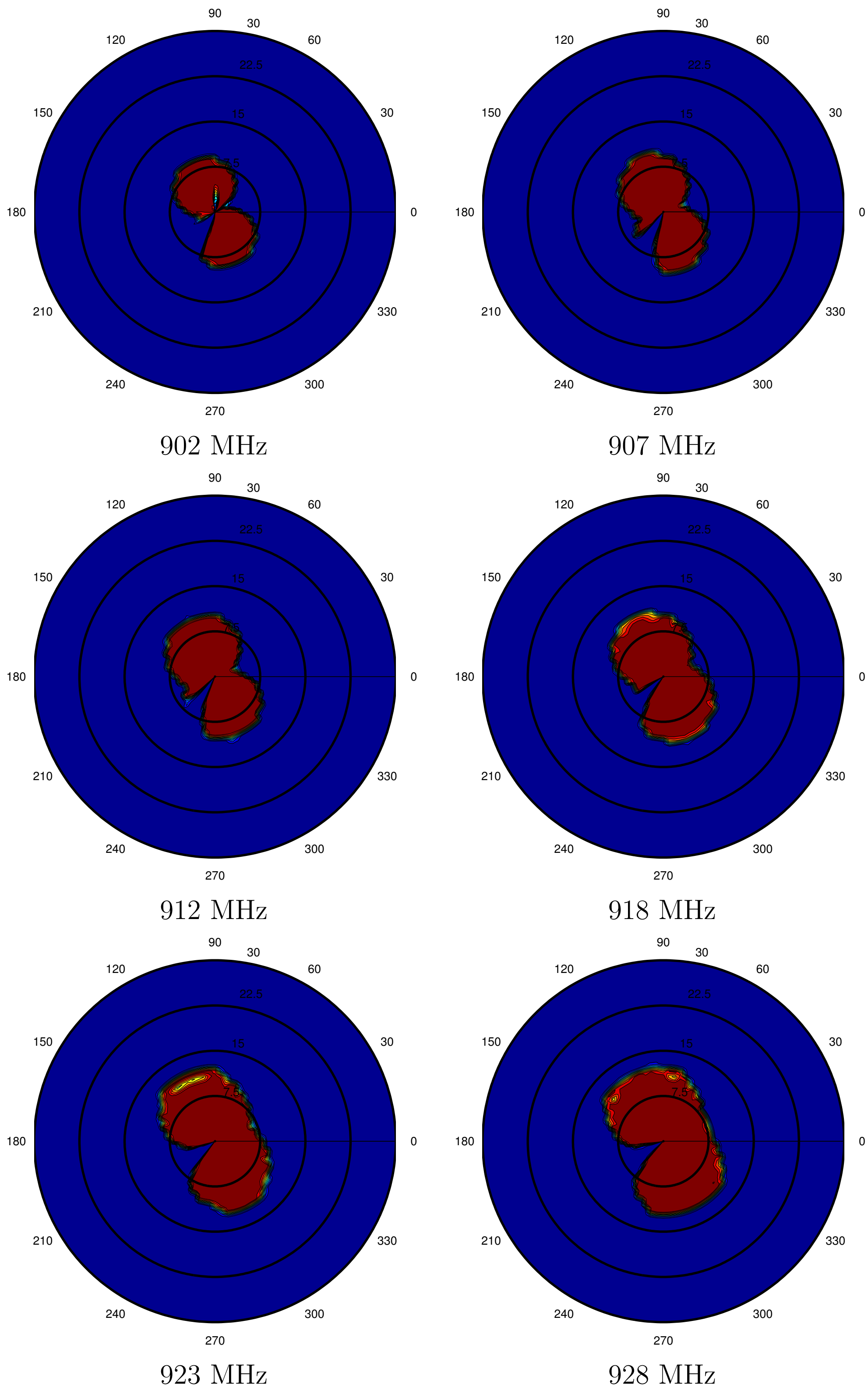
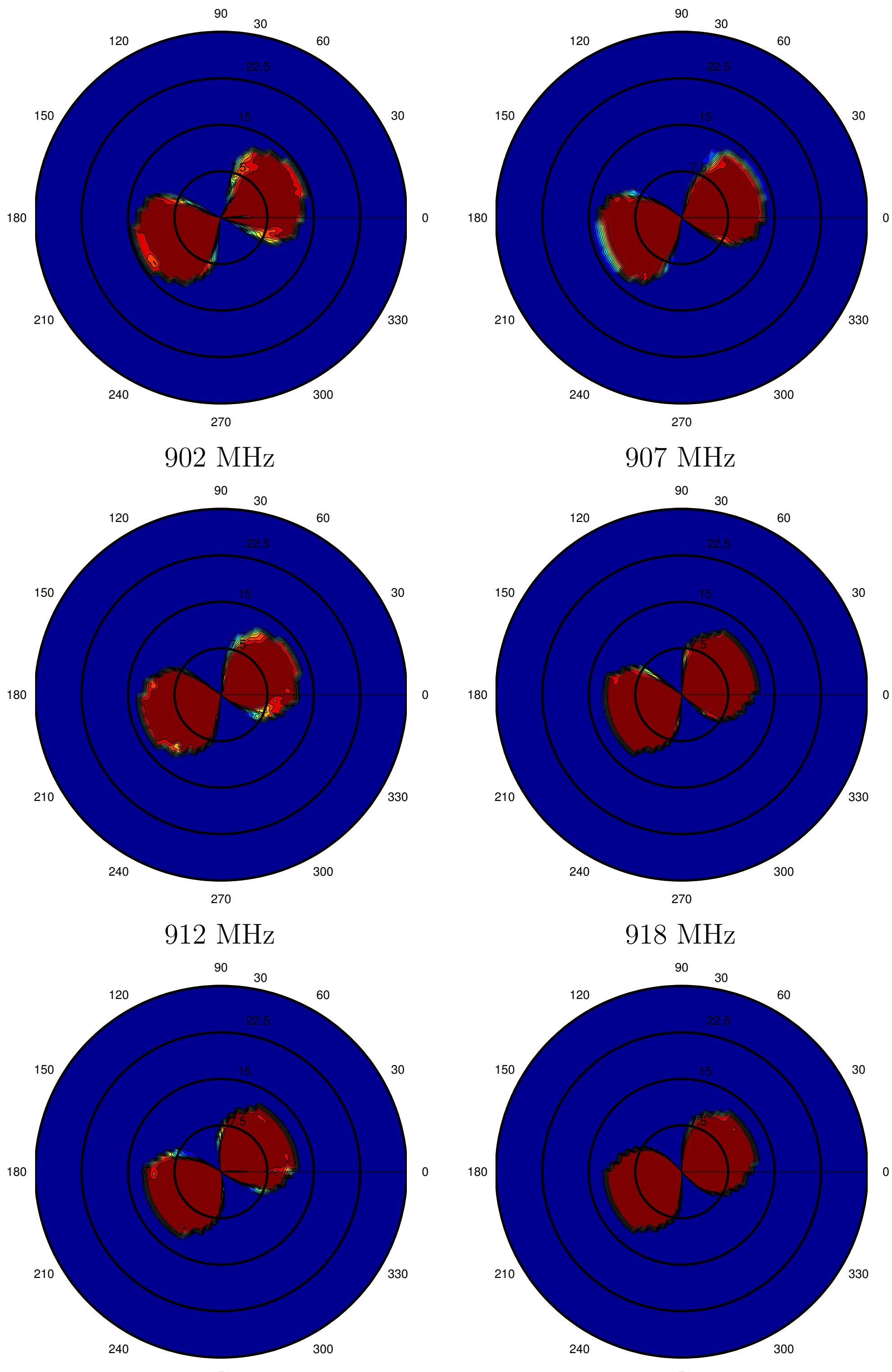


Figure 32: Radiation pattern of Avery tag in H-plane, *matched configuration.*



902 MHz | 907 MHz | 912 MHz | 918 MHz | 923 MHz | 928 MHz

Figure 33: Radiation pattern of Rafsec tag in E-plane, *unmatched configuration*.

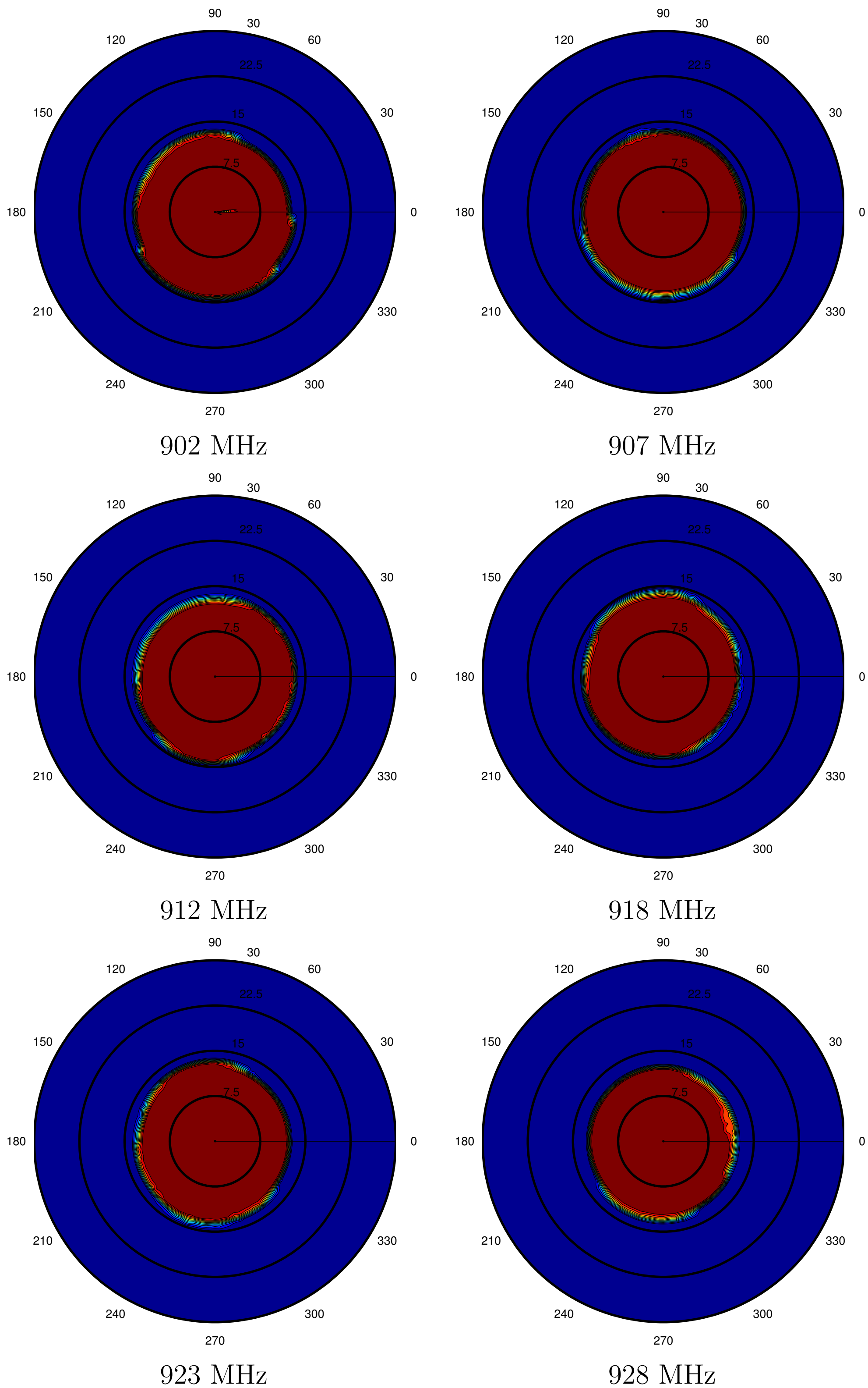
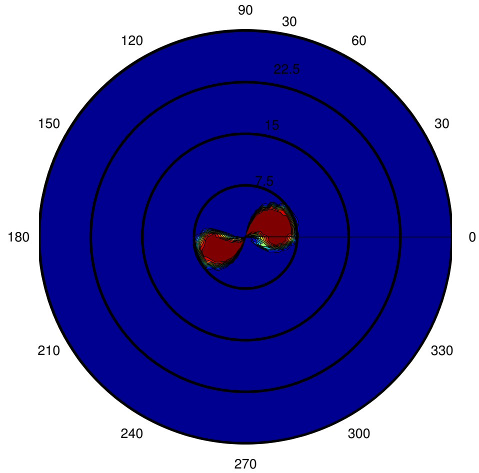
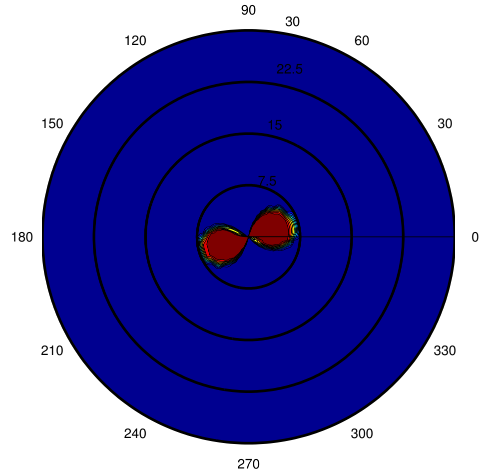


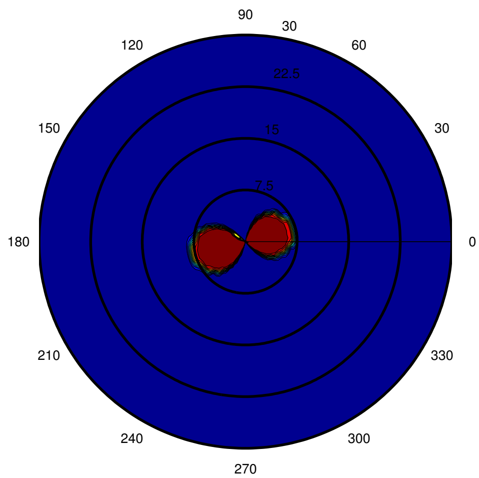
Figure 34: Radiation pattern of Rafsec tag in H-plane, *matched configuration*.



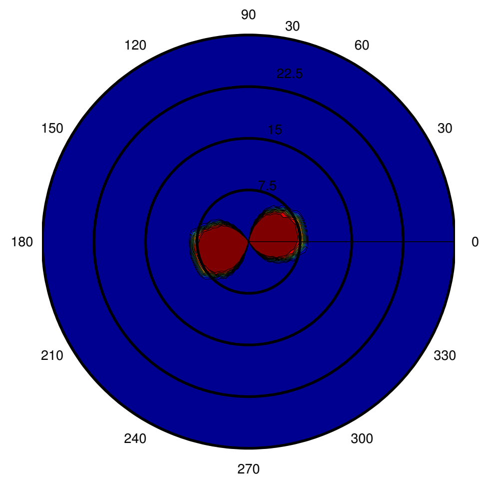
902 MHz



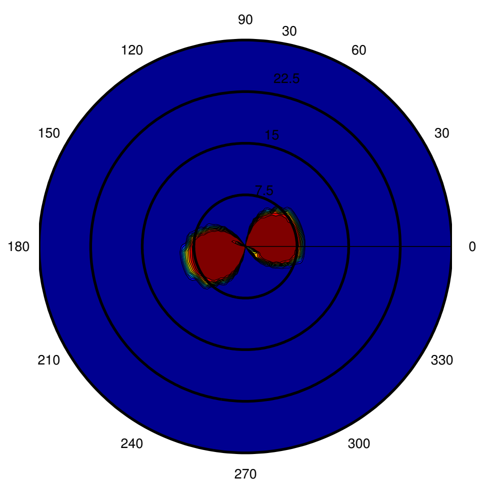
907 MHz



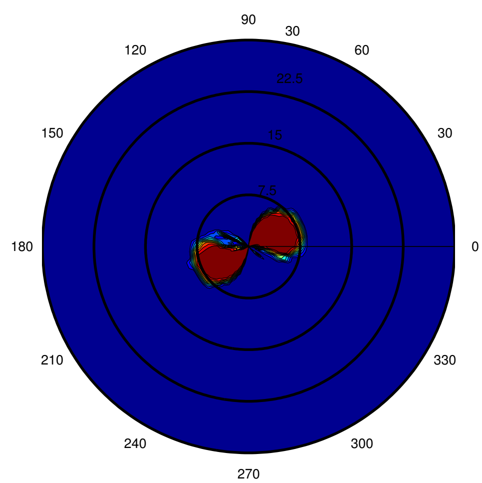
912 MHz



918 MHz



923 MHz



928 MHz

Figure 35: Radiation pattern of Symbol tag in E-plane, *unmatched configuration.*

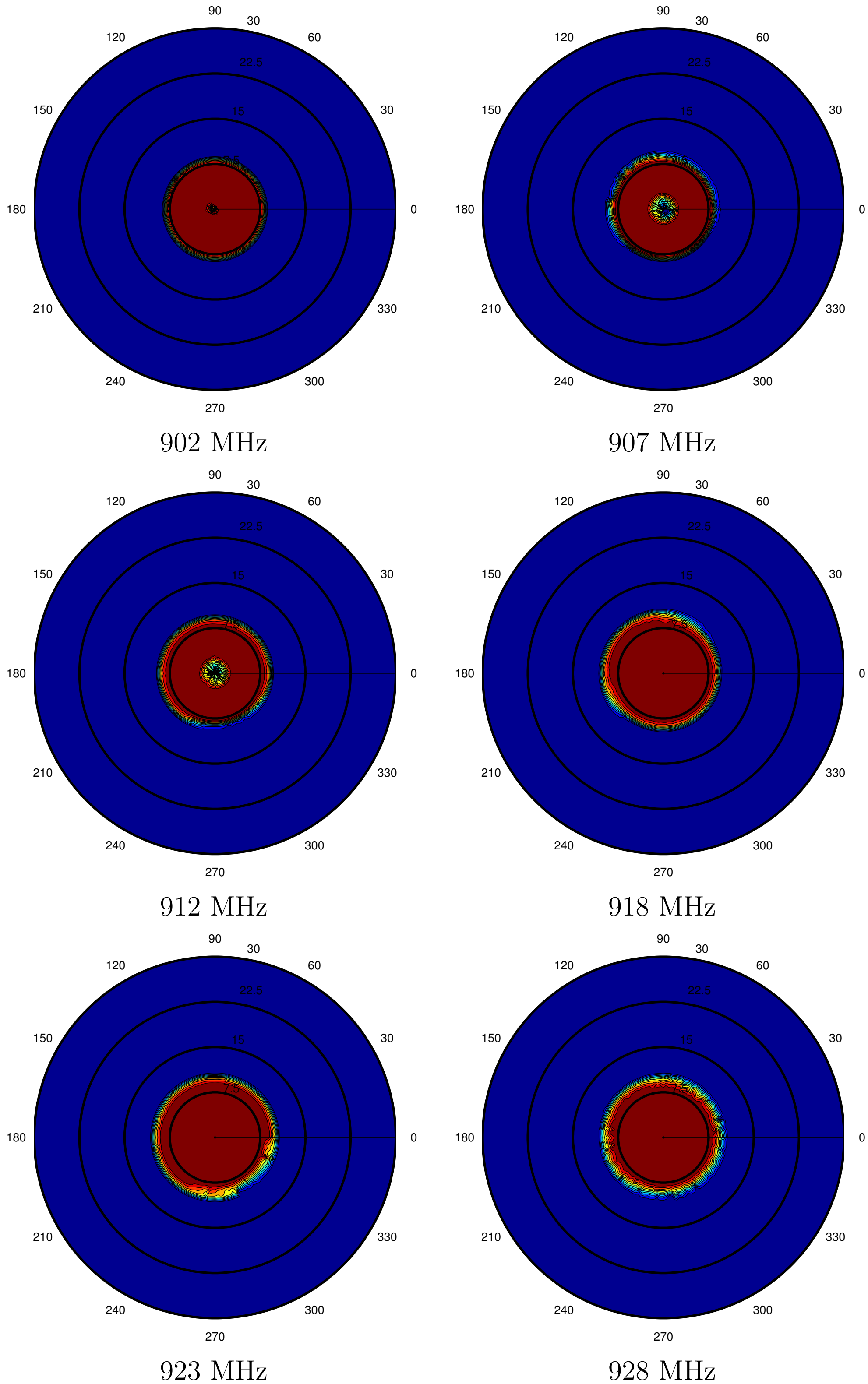


Figure 36: Radiation pattern of Symbol tag in H-plane, *matched configuration*.

6 Orientation vs. Distance

This section contains some of the most important data for the portal application to detect cell phones. It also contains some of the most surprising results. In this section, we answer the question "how far away can I detect the tag" whether the tag is in free space or on a cell phone. We begin to do this in Section 4, showing some useful results. However, in this section we no longer assume an ideal orientation between the tag and reader. We examine how the tag's orientation and distance impacts the response rate.

6.1 The Test

The test setup is straightforward and similar to that of Section 5. We place the tag centered in front of the transmit antenna, separated by a variable distance. We varied the distance from one to five feet in one foot increments. We rotated the median-performing tags of each model on both the E- and H-plane, and in five degree intervals, we performed 100 read attempts and recorded the response rate. Then we affixed the typical Rafsec tag to the cell phones and repeated the experiments. Note that all data is taken in the matched configuration.

6.2 The Data

Figures 37 through 44 show the free space performance for the Alien, Avery, Rafsec, and Symbol tags in the E- and H-planes. Next, Figures 45 through 54 show the performance of the Rafsec tag on the cell phones. The response rate follows the same color scheme presented in Figure 28.

6.3 Analysis

The free space performance of tags is not surprising, given the previous data. The Alien tag is a strong performer to well past 5 feet; the Avery tag has limited performance out to 2 to 3 feet; the Rafsec reads well out to 4 feet and is detectable at 5 feet, and the Symbol performance is about 1 foot less than the Rafsec.

The most surprising results comes from observing the performance of tags on cell phones. We actually saw the Rafsec tag on the Nokia phones actually *improve* in performance. Second, we saw the radiation of the E- and H-planes reverse; the E-plane shows a circular radiation pattern, and the H-plane shows the figure 8 pattern. Finally, we observe very little degradation in performance when the phone is between the reader and the tag. All of those results are puzzling.

We conjecture two possible explanations. First, the tag placement could be some distance above a dielectric material, and the fields generated around the antenna start to make the dipole radiate more like a microstrip. That explanation appears unlikely, given the tag's performance near metal and water (see Section 7).

Another more likely explanation is that the RFID tag is coupling to the cell phone's antenna, and if the cell phone antenna is a higher-performing antenna, what we are seeing is actually the radiation pattern of the cell phone antenna. This is quite reasonable, given that we orient the tag perpendicular to the phone. This may also explain why the tag performs

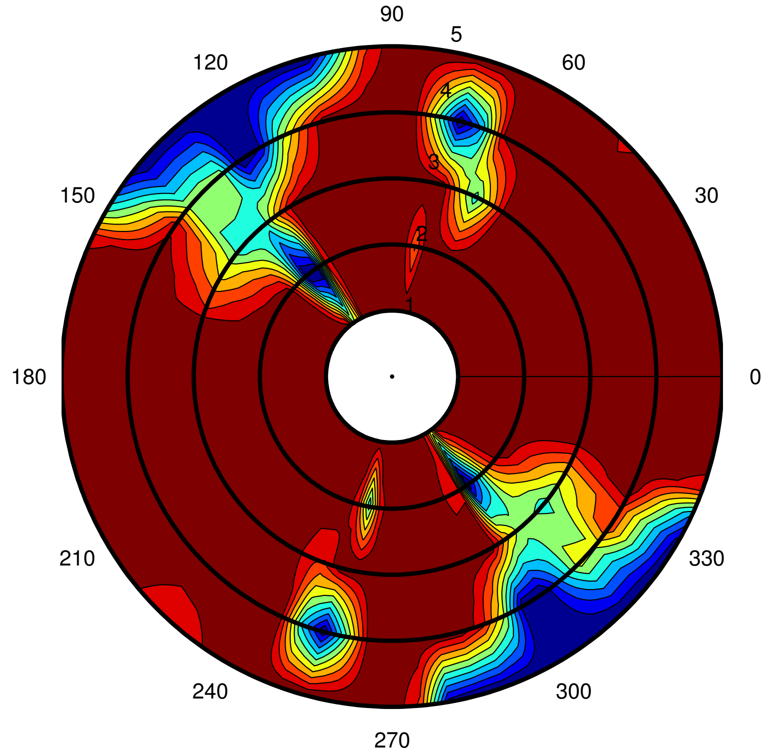


Figure 37: Alien performance vs. distance and orientation in E-plane.

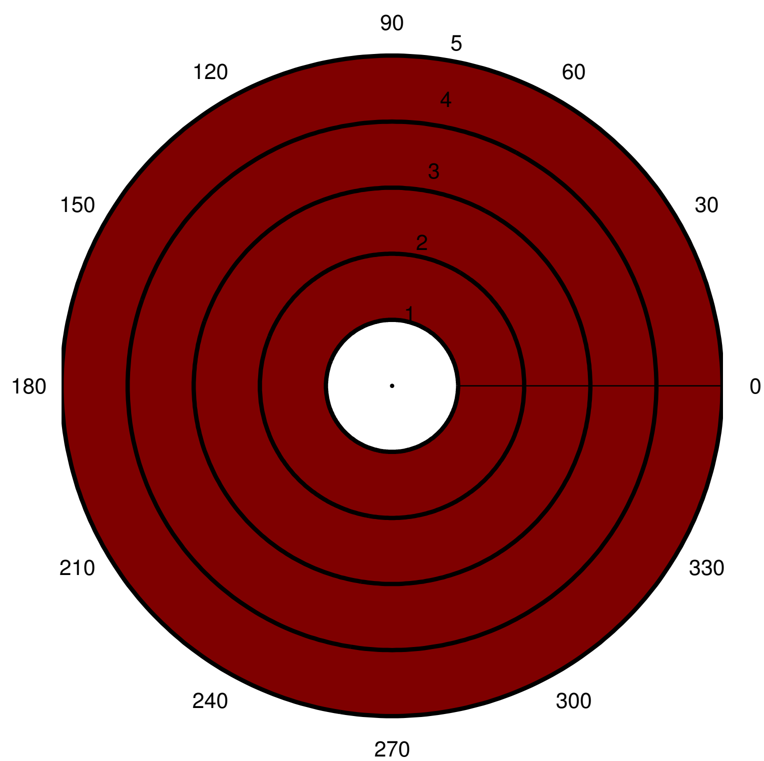


Figure 38: Alien performance vs. distance and orientation in H-plane.

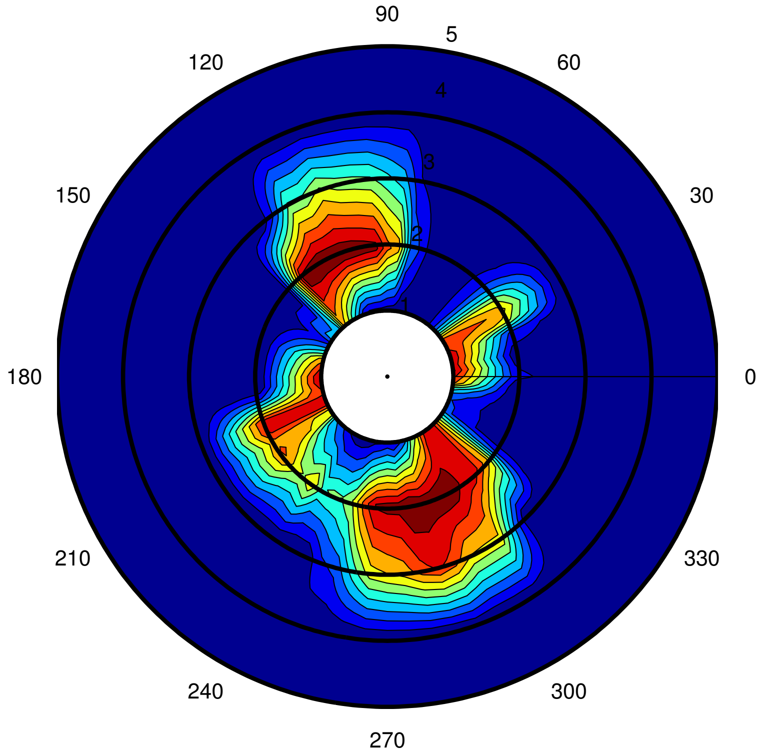


Figure 39: Avery performance vs. distance and orientation in E-plane.

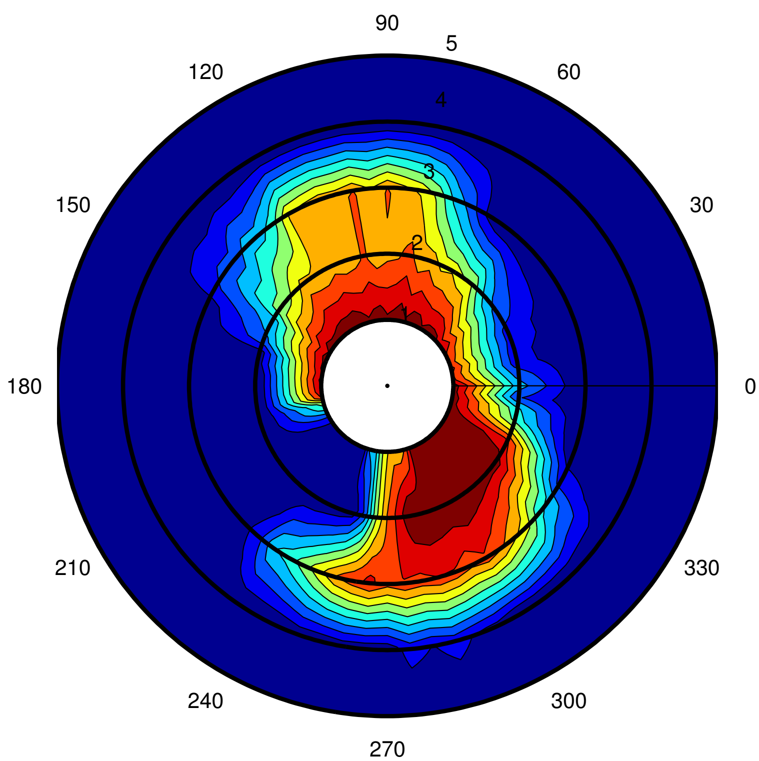


Figure 40: Avery performance vs. distance and orientation in H-plane.

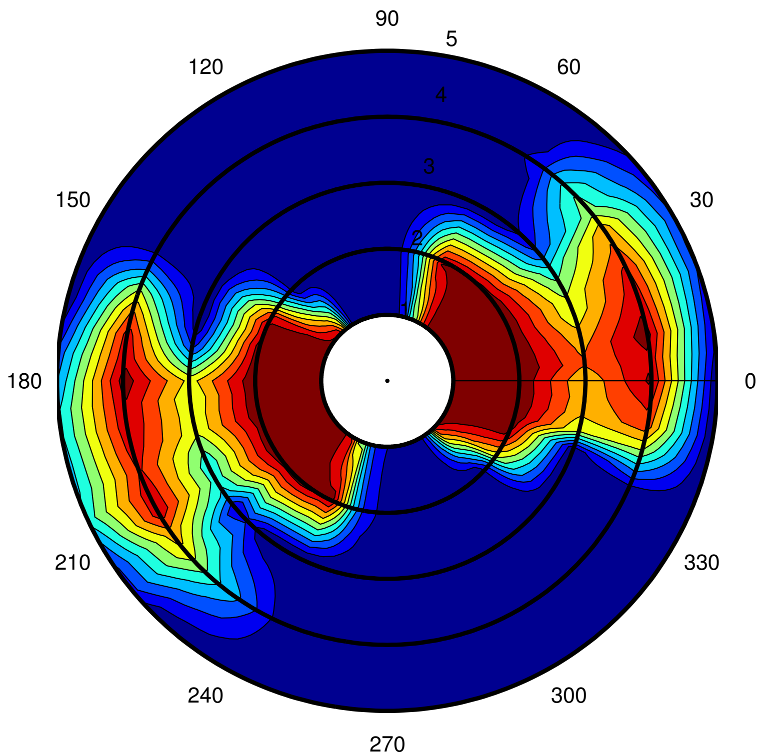


Figure 41: Rafsec performance vs. distance and orientation in E-plane.

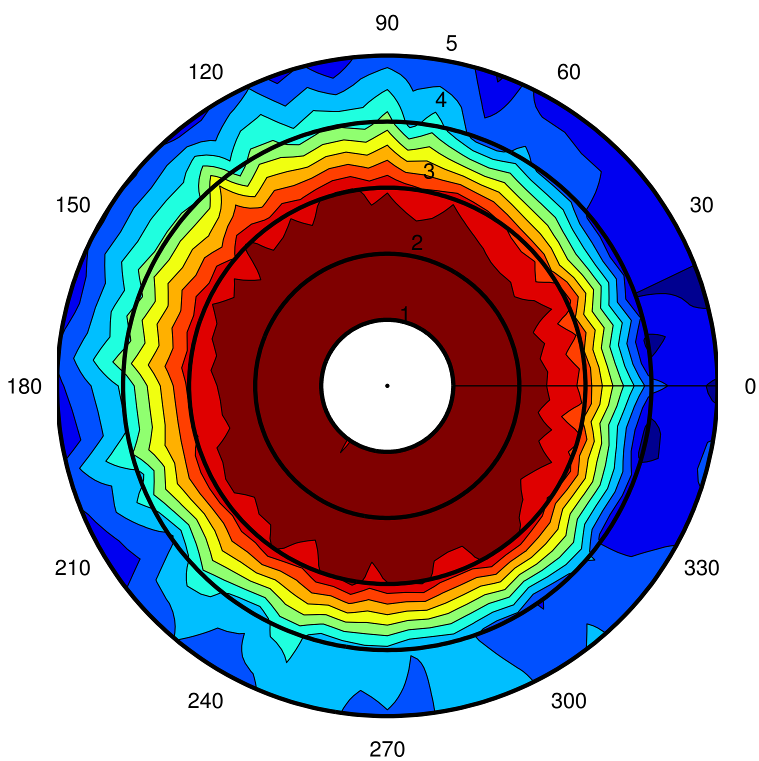


Figure 42: Rafsec performance vs. distance and orientation in H-plane.

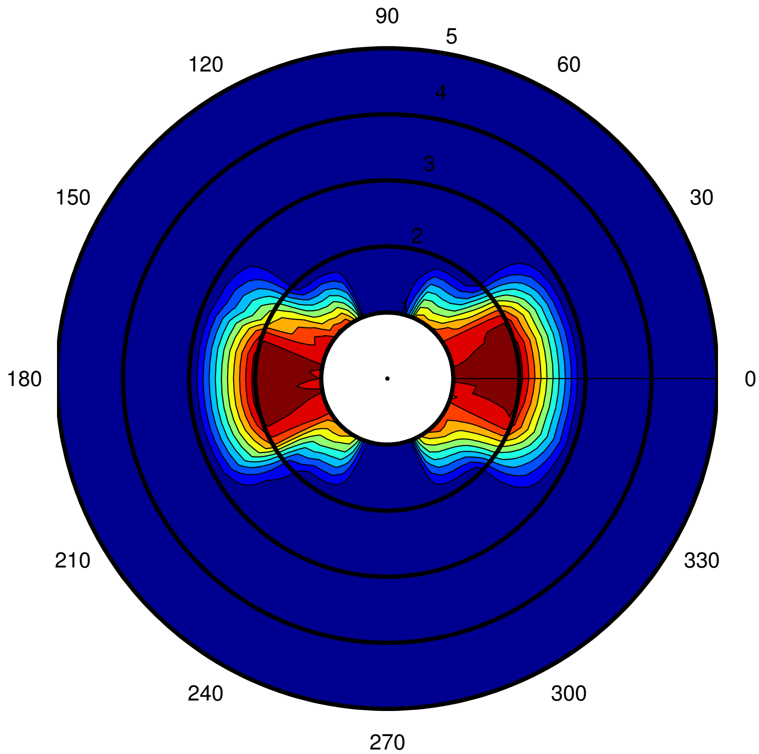


Figure 43: Symbol performance vs. distance and orientation in E-plane.

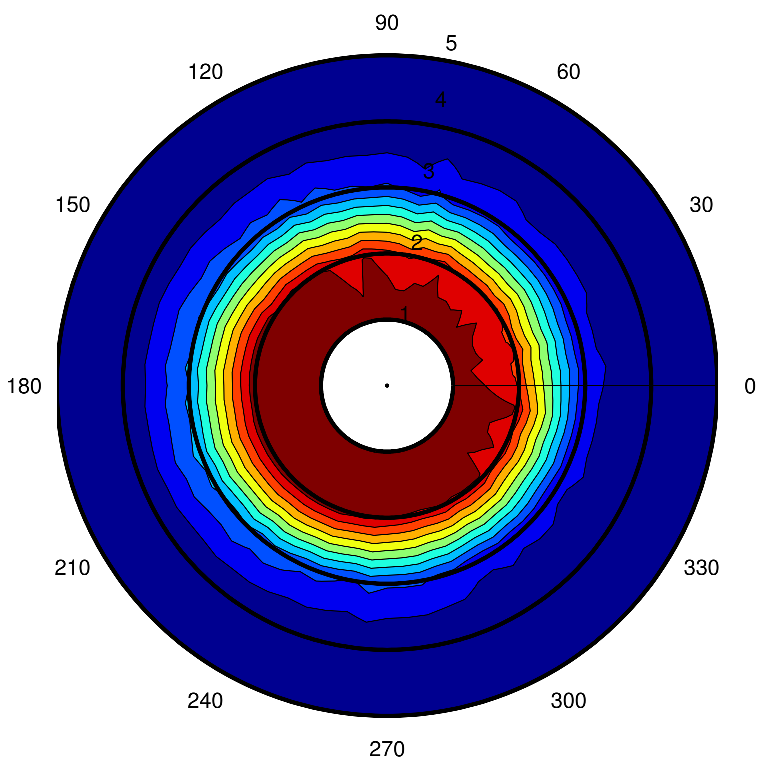


Figure 44: Symbol performance vs. distance and orientation in H-plane.

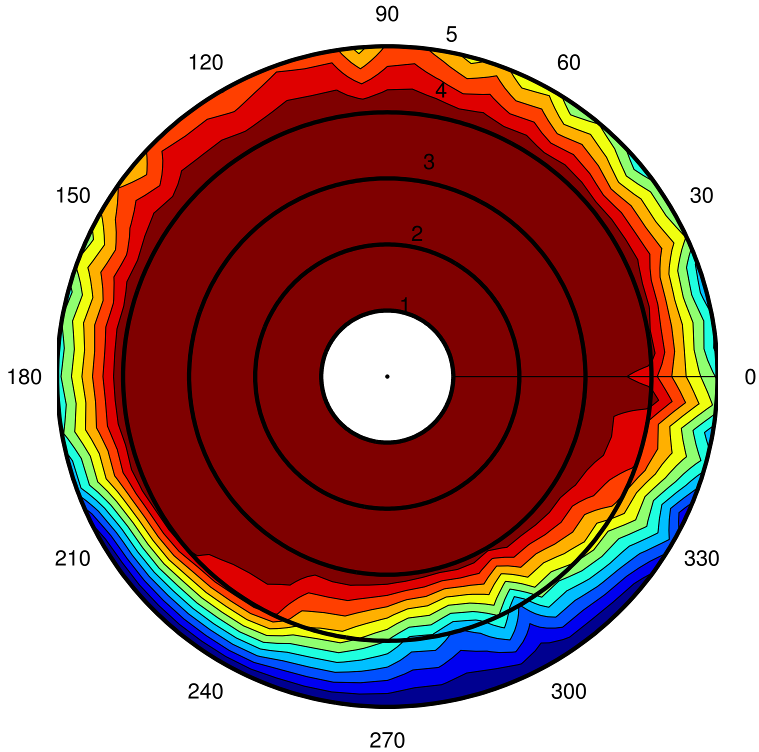


Figure 45: Rafsec on Nokia 3360 performance vs. distance and orientation in E-plane.

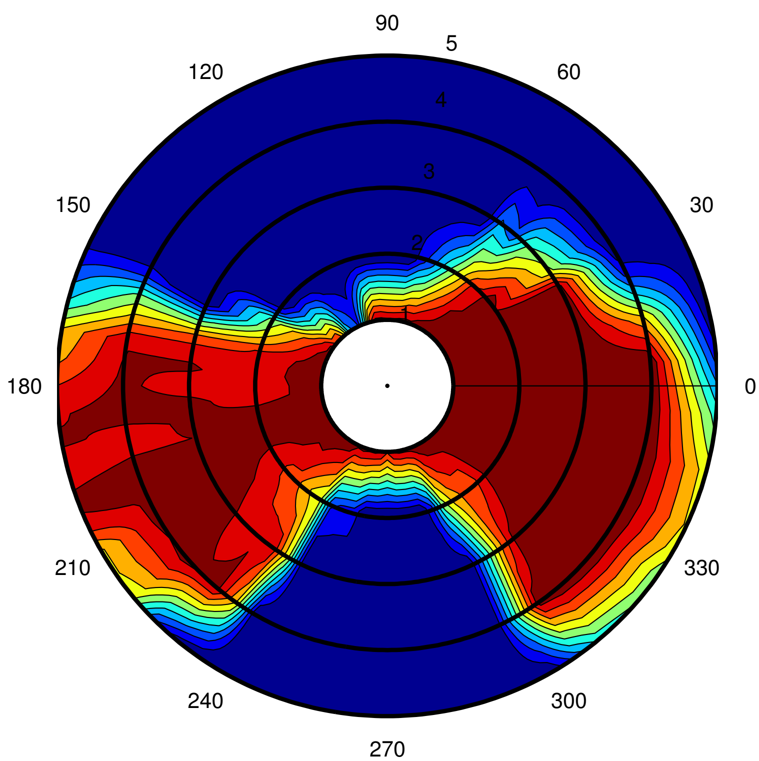


Figure 46: Rafsec on Nokia 3360 performance vs. distance and orientation in H-plane.

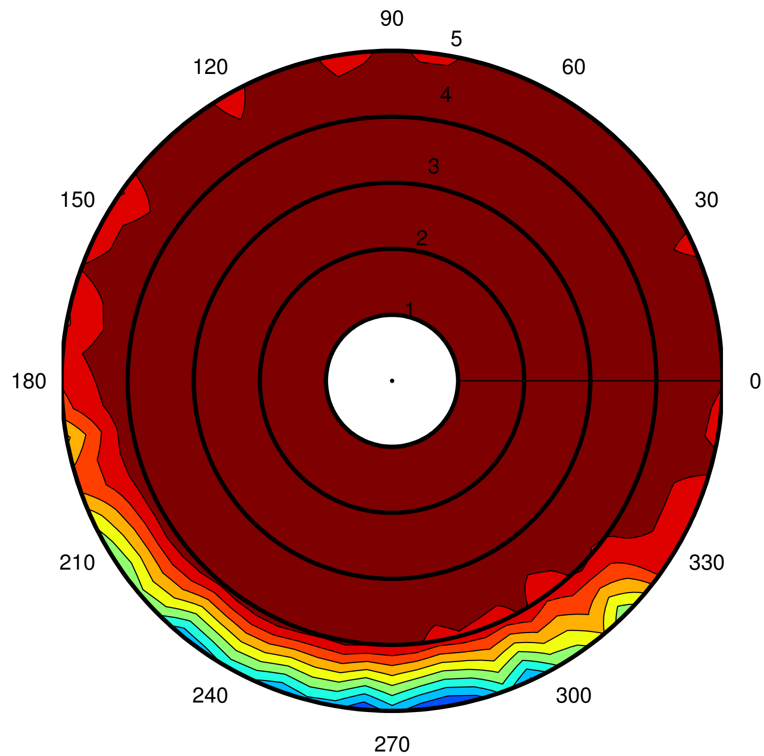


Figure 47: Rafsec on Nokia 8265 performance vs. distance and orientation in E-plane.

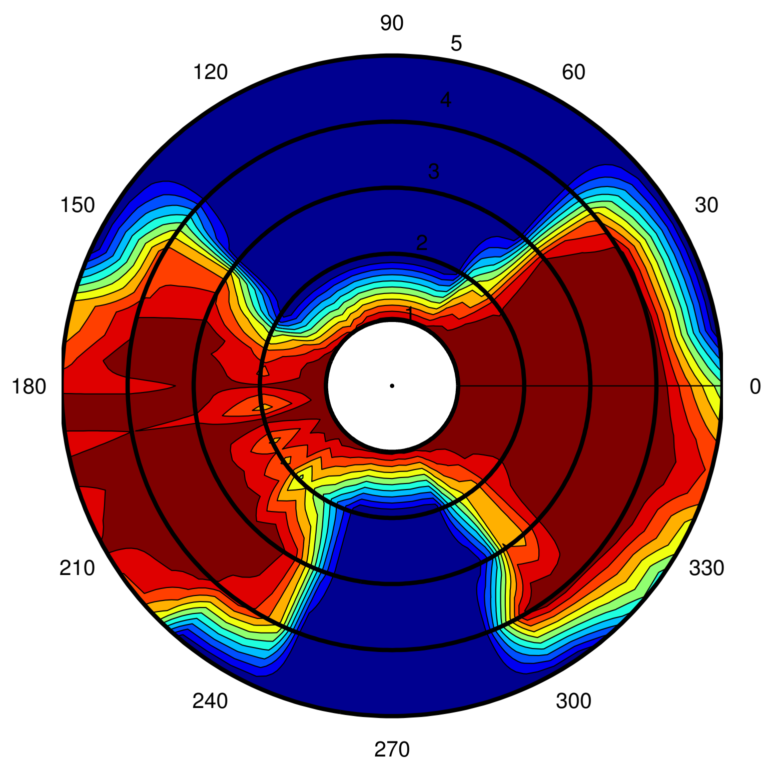


Figure 48: Rafsec on Nokia 8265 performance vs. distance and orientation in H-plane.

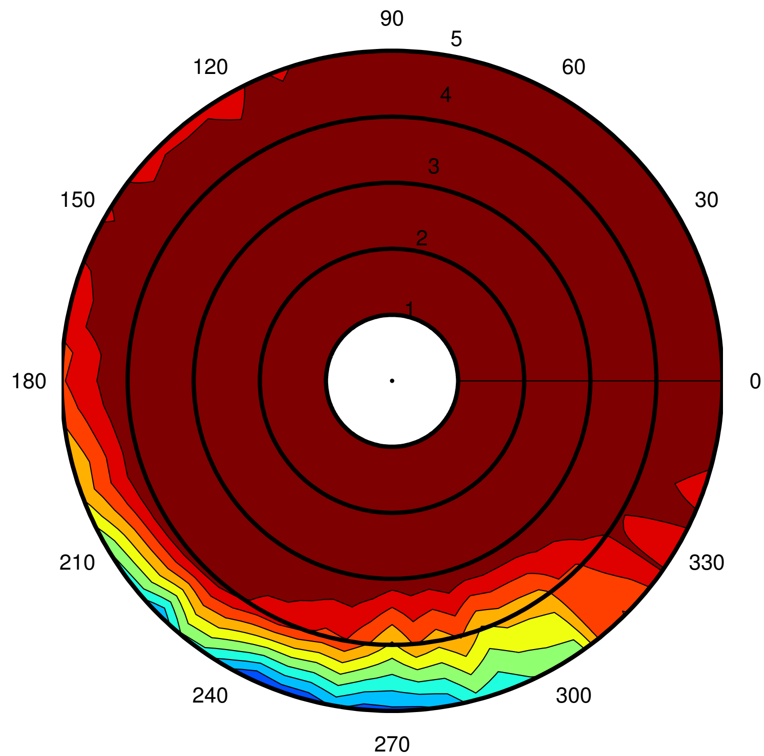


Figure 49: Rafsec on Nokia 3560 performance vs. distance and orientation in E-plane.

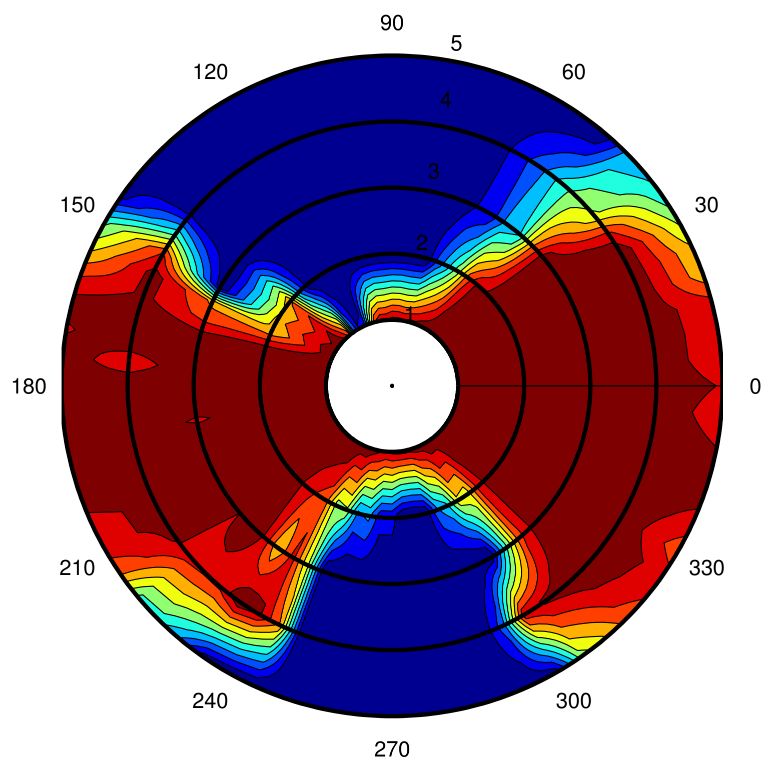


Figure 50: Rafsec on Nokia 3560 performance vs. distance and orientation in H-plane.

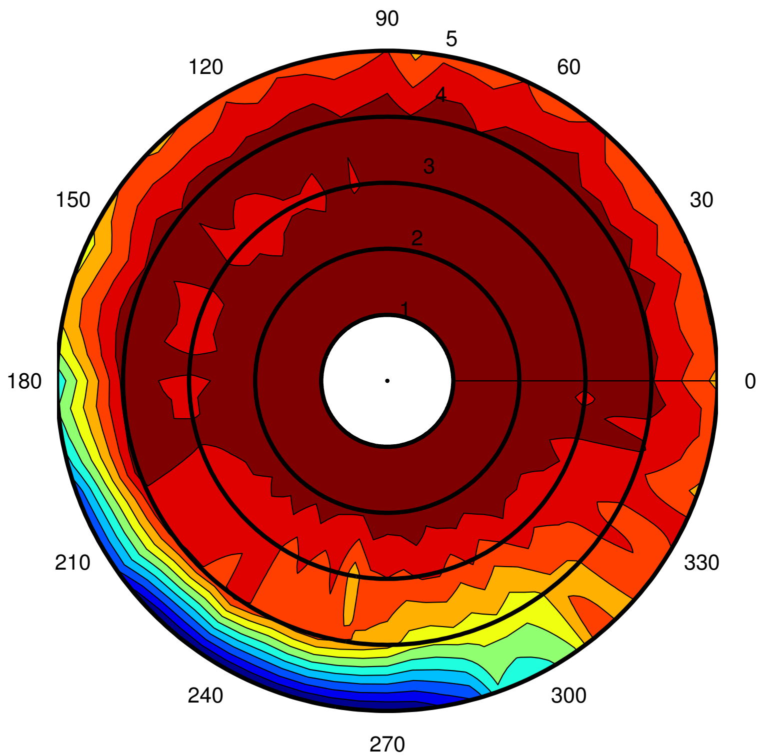


Figure 51: Rafsec on Nokia 63401 performance vs. distance and orientation in E-plane.

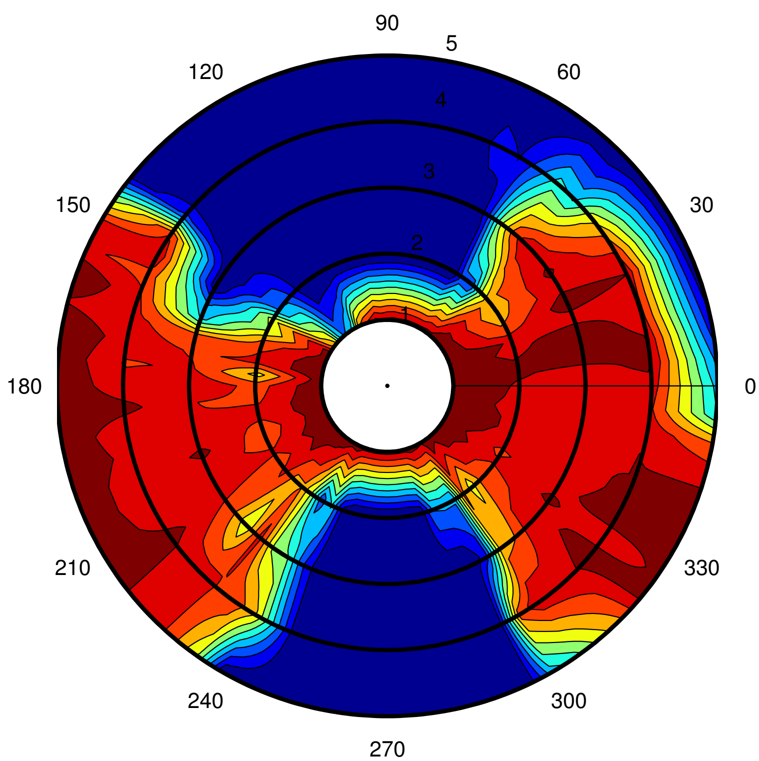


Figure 52: Rafsec on Nokia 63401 performance vs. distance and orientation in H-plane.

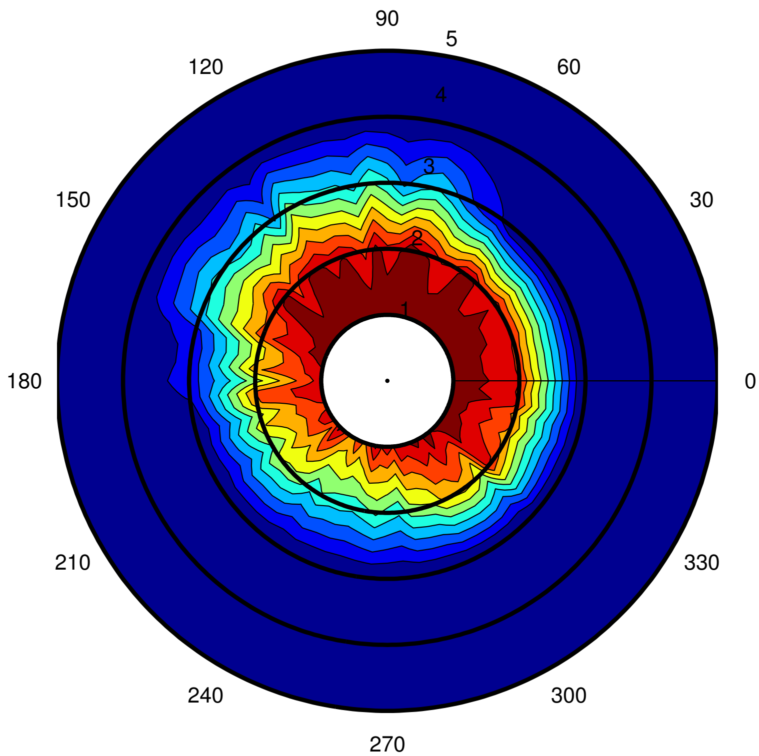


Figure 53: Rafsec on Sony T610 performance vs. distance and orientation in E-plane.

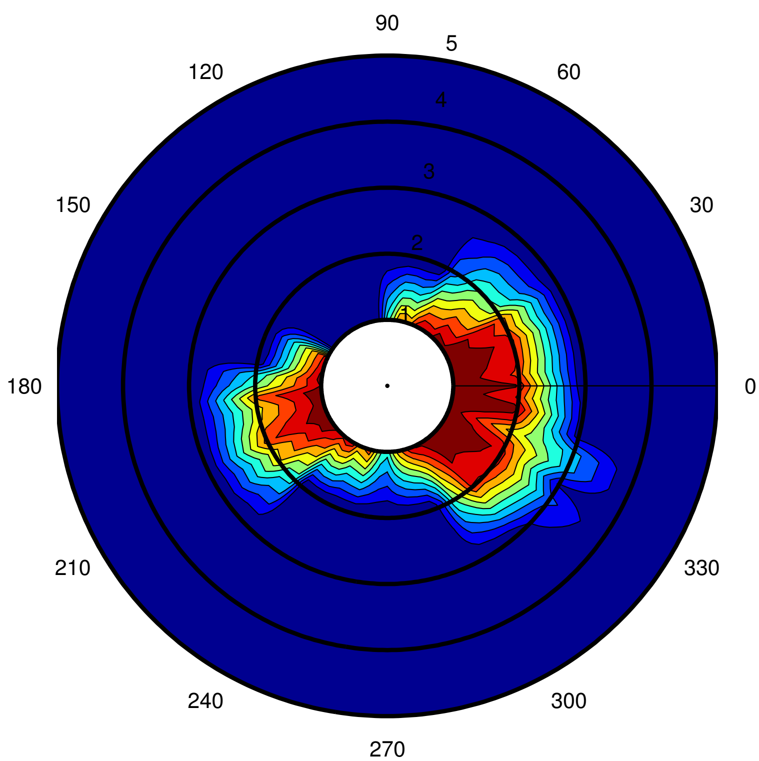


Figure 54: Rafsec on Sony T610 performance vs. distance and orientation in H-plane.

well even when the phone is between the reader and tag. If this is the case, then it could have an impact on the cell phone performance. Informal tests did not show any significant degradation in phone signal quality, but the testing was limited, and phone "power bars" may not be accurate metrics.

6.4 Conclusions

This section shows the surprising result that tags on the Nokia cell phones actually perform *better* than tags in free space. Performance, in general, is adequate for a portal using spacial diversity to overcome the nulls in the tag radiation pattern. The tag on the T610 was only slightly degraded and still usable.

7 Response Near Water and Metal

One of the challenges with UHF RFID tags is working well in the presence of water or metal. Unfortunately, the human body is made up of mostly water. Thus, if the RFID tag is placed close to the human body, performance will suffer. What we've found is that item-level RFID tags are even more sensitive to proximity to water and metal than case-level tags.

7.1 The Test

To determine how the tag performs near water and metal, we placed the median-performing tag from each model in the standard setup. The tag was positioned 12 inches from the transmit side of the antenna, parallel to the antenna, in the matched configuration. Then, we placed either a flat metal surface or a body of water held by a thin plastic container a certain distance from the tag. The reader operated at full power, and we varied the distance between the tag and the metal/water and observed the response rate.

7.2 The Data

We show two sets of data. First, we show tag performance as a function of separation from water. These are given in Figures 55 through 58. We repeat with data showing performance as a function of separation from metal in Figures 59 through 62. All data was obtained in the matched condition.

7.3 Analysis

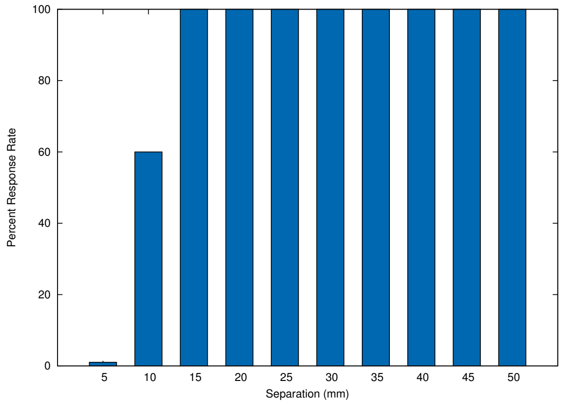
The data shows that metal is slightly more disruptive to tag performance than water, which is consistent with intuition and other results.

It is also interesting to note that the tolerance of the tag to water and metal largely correlates to free space performance metrics. We have found that this is *not* always the case, and in some tags, we have found an inverse relationship between free space performance and performance near water and metal. However, for these item-level tags, free space performance is a good predictor for performance near water and metal. For example, the Alien tag is clearly the best performing tag in free space, and it is also has a clear performance advantage when placed near water and metal. The Rafsec has a small advantage on the Symbol tag, with the Avery performance considerably worse.

The bad news is that for any tag but the Alien, there needs to be considerable separation of the tag from water in order to perform. The Rafsec, for example, shows degraded performance as near as two inches from water.

7.4 Conclusions

This section clearly illustrates the limitations of passive UHF RFID tags. For the cell phone portal application, we see that the Rafsec tag that is facing inwards and is close to the human body will be virtually unreadable. However, facing outwards, the Rafsec tag has sufficient separation and will likely be detected. However, any metal near the tag, such as keys or coins, may also cause the tag to be undetectable.



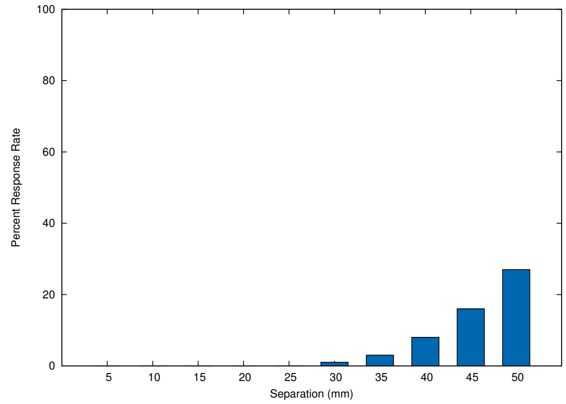
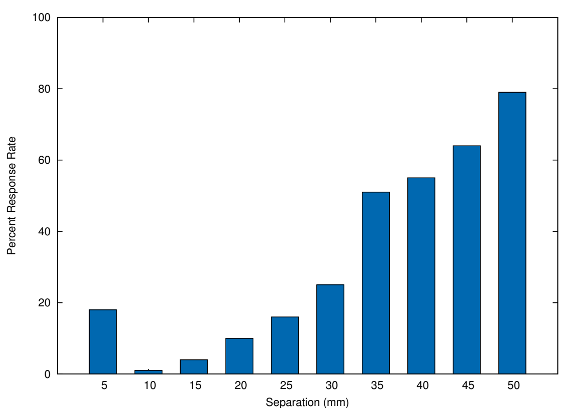


Figure 55: Alien response rate near water. Figure 56: Avery response rate near water.



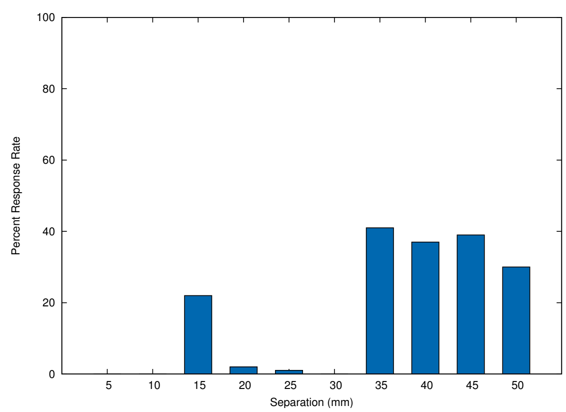


Figure 57: Rafsec response rate near water. Figure 58: Symbol response rate near water.

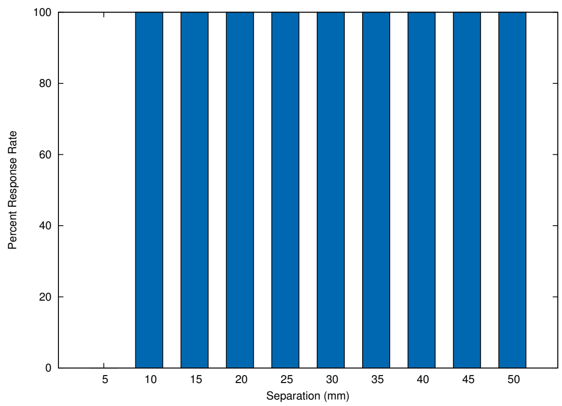


Figure 59: Alien response rate near metal.

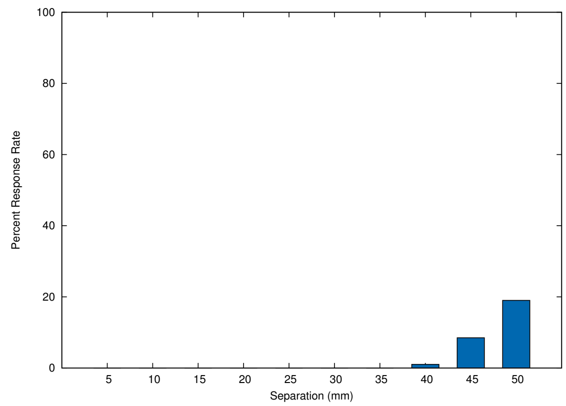


Figure 60: Avery response rate near metal.

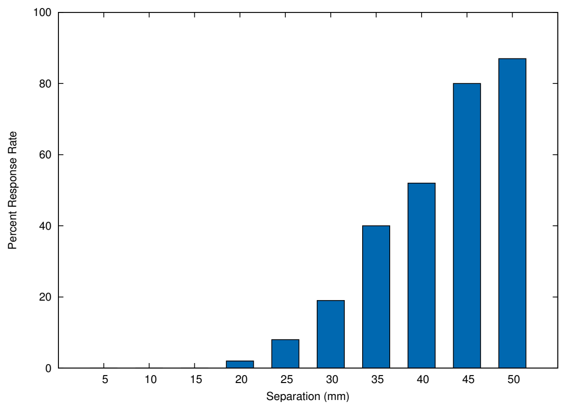


Figure 61: Rafsec response rate near metal.

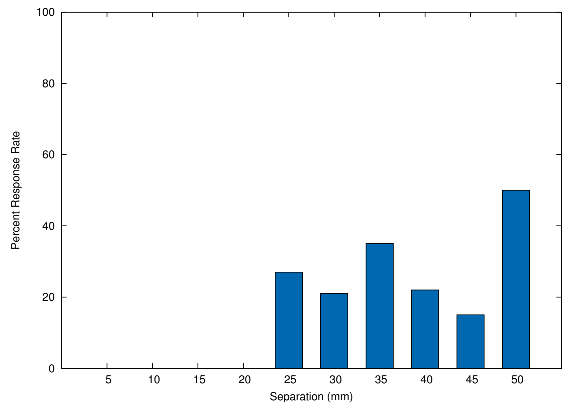


Figure 62: Symbol response rate near metal.

8 Conclusions

Our findings show that there is a passive UHF RFID solution for cell phone detection using the Rafsec item-level tag.

We studied the polarization of the ThingMagic high performance circularly-polarized antennas, and we found that there was a small amount of cross polarization present. However, when we tested the antennas with tags in different configurations, we found substantial differences in performance. From that result, we recommend good polarization diversity for a portal solution.

We found obtaining tags particularly difficult, except for the Rafsec tag. We were able to find suitable placement on the phones only with the Rafsec tag. Thus, we recommend using Rafsec tags for tagging some cell phones. We have not done any formal studies that shows whether RFID tags on a cell phone degrades the performance of the cell phone.

Variance in tag performance and yield are important issues that should be addressed through careful screening. Only the Symbol tag performed well on those metrics. Before deploying, tags should be tested for adequate performance (not just that they "work"), and after they are deployed, they should also be periodically tested to verify whether the tag still works. (We did not perform any durability studies, but it is well known that the IC does not react well to electro-static discharge.)

For all the tags but the Rafsec, we saw some interesting frequency-based behavior, but none of the unusual behavior is substantial enough to warrant concern. A portal utilizing spacial diversity should be adequate for high probability of detection.

When we studied distance and orientation, we saw excellent performance with the Alien tag, with the Rafsec and Symbol as middle performers, and the Avery tag substantially lower performing. Performance of the Rafsec tag seemed good out to 3–5 feet with most orientations, but with the read distance going to less than 1 foot at some orientations. On the Nokia phones, the performance of the Rafsec tag increased by 1 foot or more, but was worse on the T610. These measurements should be adequate for the intended application.

One must be careful to manage the power levels of the reader. Exceeding FCC regulations may sound like an easy way to achieve better performance, but many of our experiments in the unmatched configuration show that increased power may actually decrease performance in some circumstances. Thus, we recommend caution and extensive experimentation before pursuing higher transmission power.

Overall, we were surprised by the relatively good performance of UHF item-level tags. Previous experience of poor performance in item-level tags made us skeptical, plus with any small amount of detuning that might occur when placed on a cell phone, the initial pessimistic appraisal to be dismal. We did not find that to be the case. Rather, with many of the Nokia phones we found the performance to increase rather than decrease. The newer generation of Class 1 chips do provide substantially better performance than previous generations, and we anticipate that Gen 2-based tags will have even better performance.

8.1 Recommendations

Based on our findings, we recommend the Rafsec tag for the following reasons:

- Tag has suitable size so that it can be placed on phones.

- Second best performer in free space and near metal and water.
- Good availability.
- No frequency-dependent behaviors of concern.

The concerns with the tag are as follows:

- Performance is poor at 953 MHz. This should not be a concern for a fixed installation in North America.
- Moderate yield at 84%. This requires careful screening of tags before deployment.
- Dipole-like radiation pattern gives two significant nulls in the E-plane. Spacial diversity using multiple antennas should overcome this limitation.

8.2 Lessons Learned

There are a number of lessons to be learned from this work. First, we were surprised by the fact that these smaller tags were not strongly forward-link limited. That has a number of implications with regard to test procedures. The most important of those is that a small amount of cross-polarization in the reader antenna can have an unexpectedly large impact on performance.

From the data data, we can surmise that increasing the reader output power does not always boost performance, and in some very realistic cases, can actually substantially *decrease* performance. This result does not follow theoretical predictions based on simple signal power analysis, so it is likely due to some complexities of the reader. Perhaps the reader is not able to separate signal reflected by the tag from signal reflected by other objects, or perhaps the change in radar cross signature of the tags is not ideal and reaches saturation.

8.3 Future Directions

Obtaining and testing more item-level tags that fit the profile requirements are certainly feasible, as long as we can obtain the tags (which was the major impediment to this effort).

Because the reader-tag system is balanced, we are also considering revising our test procedures for the item-level tags. For example, we may have one test case that tests tag response rate and position a receiver antenna to maximize the chance of the reader perceiving the response. Another test case may determine the sensitivity of the reader and the reverse channel communication capacity.

The future of item-level passive UHF RFID tags is uncertain. While ideally they give good read distance in a small package, they are "fragile" devices. Water and metal close to the tag very quickly detunes the antenna, for example. The forward and reverse channels have little excess capacity for robustness.

A future effort might be directed at determining the suitability of higher power levels and antennas / reader matches to improve probability of detection.

There seems to be growing momentum towards HF tags for item-level tagging. Although the read distance is shorter, on the order of 3 feet or so, the system is also much more robust. They suffer less from interference from water and metal, for example, and may be more appropriate for this application.

For this simple application, there are a number of electronic article surveillance (EAS) products that would perform better than UHF RFID. For example, there are a number of products that work at HF and LF frequencies that would be much more robust. They would not be able to give a unique ID, but they would offer a much more robust solution.

Finally, one could consider developing special "metal-mount" RFID tags with small form factors. While these tags are designed specifically to work on metal, they can in fact work on any substance, such as water. The RFID Alliance Lab has already obtained full funding for the development of large (approximately 4 inch long) metal-mount tags. Item-level metal-mount tags would be on the order of 2 inches long or less (performance will be proportional to size), and 1 inch wide or less.

In developing item-level metal-mount tags, there are two main research issues. The first is getting good performance across the entire 902–928 MHz frequency spectrum used in the US, which is a significant challenge. The second is in designing the tag in such a way that it can be efficiently manufactured. We believe that we can achieve both goals. We are already working on developing similar products, have obtained some preliminary, demonstrable successful results, and are are aggressively pursuing ways to obtain intellectual property protection, as well as business strategies for commercialization.