University of Rochester

Color Bar Codes for Mobile and Other Applications

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Emerging Barcode Applications

- Link physical world to online information

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Barcodes For Mobile Applications

- Common Barcodes: Typically black&white

Aztec Code | QR Code | Data Matrix

- Color QR Codes: Capture devices already in color
  - Increase in encoding rate per unit area
    - Smaller barcode
    - "Click" count with additional data
  - Higher Robustness, better aesthetics

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Existing Color Barcodes For Mobile Applications

- Encode In Color (i.e. R,G,B,C,M,Y,K,W)
  - Microsoft Color Barcodes[Jancke2006] and ColorCodes[Kato2010]
  - Sensitive to inter-separation misregistration (-)

change in color

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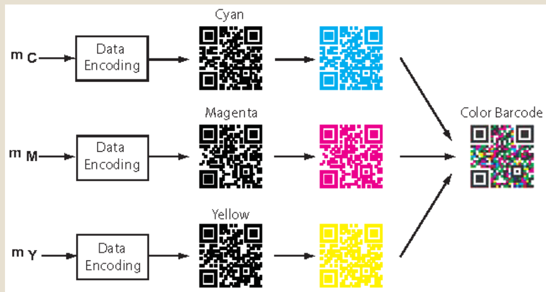
Per-Colorant Data Encoding

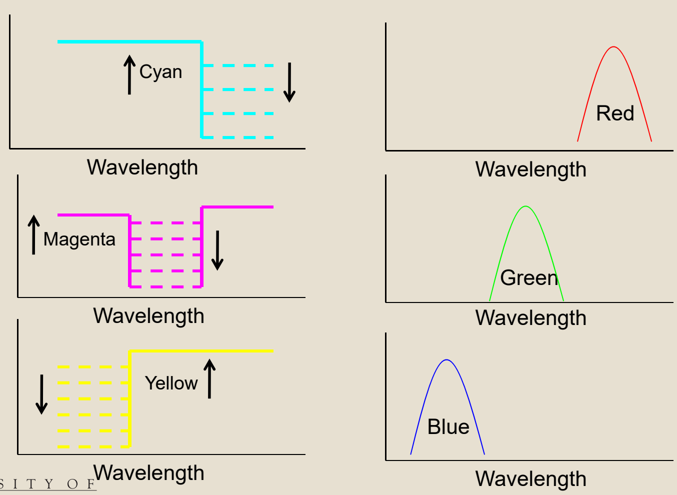


- Generalizes commonly used monochrome barcodes to color
  - Adopts components from monochrome counterpart
  - Higher encoding rate (x3)
- Robustness against inter-separation misregistration
- Challenge: Color interference

H. Blasinski, O. Bulan, and G. Sharma, "Color barcodes for mobile applications: A per channel framework," *IEEE Trans. Image Processing*, vol. 22, no. 4, Apr. 2013, pp. 1498-1511.

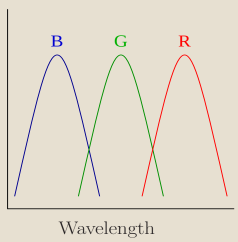
Color Separation: Print and Capture

- Idealized Color Printing-Scanning System:

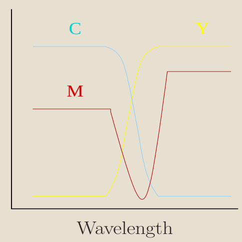


Color Separation

- In reality:



(a)



(b)

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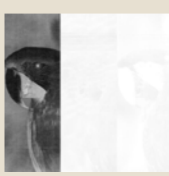
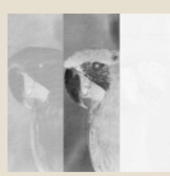
Color Interference

- In reality:


CMY Striped Print


Scan R channel


Scan G channel


Scan B channel

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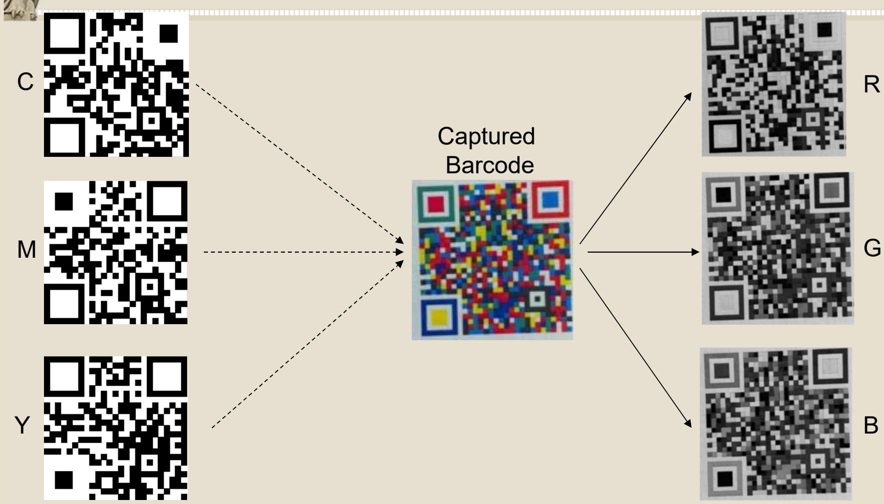
Color Interference



- Simple thresholding not sufficient!!!

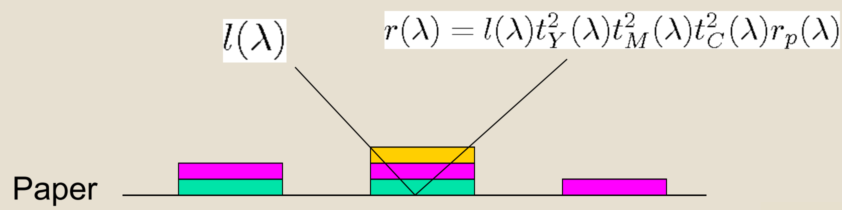
Color Interference Variation

- Interference variation with printer, capture device, illumination etc.
- Removal on the fly required

Our Approach For Color Interference Cancellation

- A physical model for print-capture process
  - Model parameters dependent on printer, capture device, and illumination
- Estimation of model parameters:
  - Pilot Block
  - EM-Style
- Estimating print-channels using the scanned barcode and the estimated model parameters

Physical Model For Reflectance From Barcode Substrate



- Reflectance of the printed barcode

$$r(x, y; \lambda) = r_w(\lambda) 10^{-\sum_{i \in \{C,M,Y\}} d^i(\lambda) I_i(x,y)} \qquad i \in (C, M, Y)$$

$I_i(x, y)$

Physical Model For Capturing

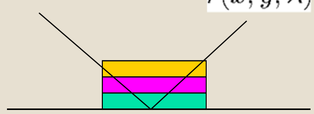
$I_k^s(x,y)$ $\quad k \in (R,G,B)$

$r(x,y;\lambda)$

$$I_k^s(x,y) = \int s_k(\lambda) r(x,y;\lambda)\, d\lambda$$

$\alpha_k \delta(\lambda - \lambda_k)$

Paper



- The captured image at the kth scan channel

$$I_k^s(x,y) = \alpha_k r(x,y;\lambda_k) = \alpha_k r_w(\lambda_k) 10^{-\sum_{i\in\{C,M,Y\}} d^i(\lambda_k) I_i(x,y)}$$

$$= I_k^s(W) 10^{-\sum_{i\in\{C,M,Y\}} d^i(\lambda_k) I_i(x,y)}$$

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A Linear Relation Between Print and Scan Channels

- Logarithmic transform of scan channels

$$d_k(x,y) = -\log_{10}\left(\frac{I_k^s(x,y)}{I_k^s(W)}\right) = \sum_{i\in\{C,M,Y\}} d_i(\lambda_k) I_i(x,y)$$

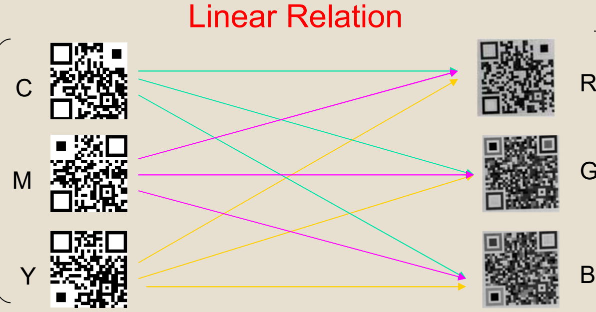
$$\mathbf{d} = \mathbf{D}\mathbf{I}$$

Linear Relation

Print colorant channels

Optical density from scan channels

$\mathbf{I}$



$\mathbf{d}$

$\mathbf{D}$ 3x3 Transformation Matrix (Unknown)

Need to estimate

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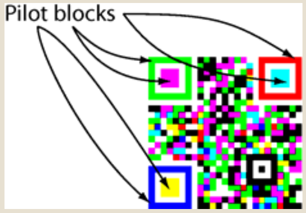
Estimation of Transformation Matrix

- Pilot Block Approach
  - A smart design of synchronization marks



  - Least Squares estimate of $\mathbf{D}$

$$\min_{\mathbf{D}} ||\mathbf{D}\mathbf{I} - \mathbf{d}||^2$$

Calculated for pilot blocks

Known for pilot blocks

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Color Interference Cancellation

Optical density from scan channels

$$\mathbf{d} \times \mathbf{D}^{-1} =$$

Estimated print colorant channels

Estimated using pilot blocks

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Final Thresholding

- Local Thresholding
  - Locally determines threshold to account for lighting variations
- Fixed Thresholding
  - Use a fixed threshold for all channel
- Adaptive Thresholding
  - Use pilot blocks to assign a threshold for each channel

Estimated C — Estimated M — Estimated Y

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Experimental Set-up

- Multiple Smart-phones and Printers

(a) Phones

ID	Make and model	Sensor size, MP	Autofocus
1	LG Ally[1]	3.2	✓
2	iPhone 4	5.0	✓
3	iPhone 3GS	3.0	✓
4	iPhone 3G[1]	2.0	
5	Nokia C6	5.0	✓
6	Samsung Intercept	3.2	✓
7	Motorola Droid X	8.0	✓
8	Motorola Droid	5.0	✓
9	Blackberry 8900 Curve	3.2	✓
10	Nokia N900	5.0	✓
11	LG VX9900[2]	2.0	✓

(b) Printers

ID	Make and model	Laser	Inkjet
1	HP OfficeJet 6500		✓
2	HP Color LaserJet 4700	✓	
3	Ricoh Aficio MPC2550	✓	
4	HP Color LaserJet 4650	✓	
5	Epson Stylus NX215		✓
6	Dell Printer 948		✓
7	Xerox WorkCentre 7665	✓	
8	Xerox Phaser 8860[3]		✓
9	Ricoh Aficio MPC4501	✓	
10	HP Color LaserJet 5550	✓	

- Metrics for Performance Evaluation
  - Bit error rate (B)
  - Synchronization rate (S)
  - Decoding rate (D)

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Experimental Set-up

- Images captured under typical lighting conditions (indoor, outdoor, fluorescent, incandescent)
  - Captured apprx. 15 cm from the printed barcode

Experimental Results

- Separated channels with interference cancellation

Original print colorant channels

Estimated print colorant channels without cancellation

Estimated print colorant channels with cancellation

Experimental Results

- Bit Error Rate (B) and Synchronization Rate (S) Performance
  - QR code

Size		Estimated yellow			
		Int. cancellation		AT	LT
		PB + AT	PB + LT		
15 mm	B	6.88	6.48	20.66	17.45
	S	82.36	82.36	82.16	82.16
20 mm	B	5.13	5.39	18.18	17.59
	S	92.60	92.60	92.60	92.60
25 mm	B	3.42	4.56	15.14	15.31
	S	91.40	91.40	91.20	91.40
30 mm	B	3.37	3.88	16.85	13.64
	S	90.16	90.16	89.96	90.16

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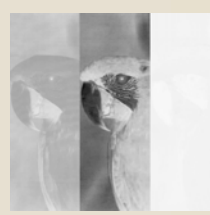
Experimental Results

- Bit Error Rate (B) and Synchronization Rate (S) Performance
  - QR code

Size		Estimated magenta			
		Int. cancellation		AT	LT
		PB + AT	PB + LT		
15 mm	B	8.37	5.69	12.28	8.71
	S	82.36	82.36	82.16	82.16
20 mm	B	5.57	4.25	10.44	7.61
	S	92.60	92.60	92.00	92.00
25 mm	B	3.11	3.03	8.77	5.76
	S	91.40	91.40	90.80	91.20
30 mm	B	2.73	2.47	7.31	4.60
	S	90.16	90.16	90.16	89.96



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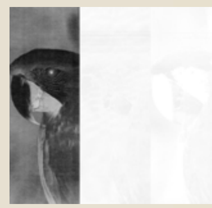
Experimental Results

- Bit Error Rate (B) and Synchronization Rate (S) Performance
  - QR code

Size		Estimated cyan			
		Int. cancellation PB + AT	Int. cancellation PB + LT	AT	LT
15 mm	B	9.23	1.72	5.09	1.49
	S	82.36	82.36	82.16	82.16
20 mm	B	5.02	0.87	2.49	2.16
	S	92.40	92.60	92.60	92.60
25 mm	B	1.21	0.55	0.57	0.47
	S	91.40	91.40	91.20	91.40
30 mm	B	0.70	0.58	0.15	0.27
	S	90.16	90.16	90.16	90.16



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Experimental Results

- Synchronization and Decoding Success Rates

EC		Estimated Cyan					Estimated Magenta					Estimated Yellow					Monochrome
		Int. cancellation PB + AT	Int. cancellation PB + LT	Int. cancellation EM	AT	LT	Int. cancellation PB + AT	Int. cancellation PB + LT	Int. cancellation EM	AT	LT	Int. cancellation PB + AT	Int. cancellation PB + LT	Int. cancellation EM	AT	LT	
L	SSR	95.56	95.56	95.56	95.56	95.56	95.56	95.56	95.56	95.56	95.56	95.56	95.56	95.56	95.56	95.56	85.19
	DSR	100	100	83.72	90.70	100	97.67	41.86	81.40	39.53	69.77	20.93	6.98	46.51	0	0	98.26
M	SSR	93.33	93.33	93.33	93.33	93.33	93.33	93.33	93.33	93.33	93.33	93.33	93.33	93.33	93.33	93.33	95.38
	DSR	100	100	85.71	92.86	100	92.86	38.10	88.10	52.38	40.48	45.24	26.19	54.76	0	0	100
Q	SSR	95.56	95.56	95.56	95.56	95.56	95.56	95.56	95.56	95.56	95.56	95.56	95.56	95.56	95.56	95.56	88.89
	DSR	97.67	100	88.37	95.35	100	93.02	34.88	81.40	55.81	58.14	30.23	44.19	58.14	0	0	100
H	SSR	95.56	95.56	95.56	95.56	95.56	95.56	95.56	95.56	95.56	95.56	95.56	95.56	95.56	95.56	95.56	87.41
	DSR	100	100	90.70	100	100	100	86.05	79.07	41.86	58.14	37.21	25.58	48.84	2.33	0	100
Total	SSR	95.00	95.00	95.00	95.00	95.00	95.00	95.00	95.00	95.00	95.00	95.00	95.00	95.00	95.00	95.00	89.16
	DSR	99.42	100	87.13	94.74	100	95.91	50.29	82.46	47.37	56.73	33.33	25.73	52.05	0.58	0	99.58

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Estimation of Transformation Matrix

- Expectation-Maximization Type Approach
  - $\mathbf{D}$ and $\mathbf{I}$ hidden and latent variables
  - Alternating minimizations to estimate $\mathbf{D}$ and $\mathbf{I}$ simultaneously

Step 1
$$\min_{\mathbf{I}} \quad \|\mathbf{DI} - \mathbf{d}\|^2 \qquad s.t. \quad \mathbf{I} \in (0,1)$$

Step 2
$$\min_{\mathbf{D}} \quad \|\mathbf{DI} - \mathbf{d}\|^2 \qquad s.t. \quad 0 \leq \mathbf{D}$$

  - Convergence guaranteed!

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Estimation of Transformation Matrix

- Expectation-Maximization Type Approach
  - Relaxation in Step1

NP Hard

$$\min_{\mathbf{I}} \quad \|\mathbf{DI} - \mathbf{d}\|^2 \quad s.t. \quad \mathbf{I} \in (0,1) \xrightarrow{\text{Relaxation}} \min_{\mathbf{I}} \quad \|\mathbf{DI} - \mathbf{d}\|^2 \quad s.t. \quad 0 \leq \mathbf{I} \leq 1$$

  - Initialization

$$\mathbf{D} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Ideal case without color interference (unity gain)

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Pilot Block vs EM-Type

- Pilot Block Approach
  - Simple and efficient (+)
  - Requires customized design (-)
- EM-Type Approach
  - General algorithm and does not require customized design (+)
  - Converges to local optima (-)
  - Slower (-)

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Experimental Results

- Synchronization (S) and Decoding Rate (D) Performance
  - QR code: 4 error correction levels (L,M,Q,H)

EC		Estimated yellow				
		Int. cancellation			AT	LT
		PB + AT	PB + LT	EM		
L	S	95.56	95.56	95.56	95.56	95.56
	D	20.93	6.98	46.51	0	0
M	S	93.33	93.33	93.33	93.33	93.33
	D	45.24	26.19	54.76	0	0
Q	S	95.56	95.56	95.56	95.56	95.56
	D	30.23	44.19	58.14	0	0
H	S	95.56	95.56	95.56	95.56	95.56
	D	37.21	25.58	48.84	2.33	0

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Experimental Results

- Synchronization (S) and Decoding Rate (D) Performance
  - QR code: 4 error correction levels (L,M,Q,H)

EC		Estimated magenta				
		Int. cancellation			AT	LT
		PB + AT	PB + LT	EM		
L	S	95.56	95.56	95.56	95.56	95.56
	D	97.67	41.86	81.40	39.53	69.77
M	S	93.33	93.33	93.33	93.33	93.33
	D	92.86	38.10	88.10	52.38	40.48
Q	S	95.56	95.56	95.56	95.56	95.56
	D	93.02	34.88	81.40	55.81	58.14
H	S	95.56	95.56	95.56	95.56	95.56
	D	100	86.05	79.07	41.86	58.14

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Experimental Results

- Synchronization (S) and Decoding Rate (D) Performance
  - QR code: 4 error correction levels (L,M,Q,H)

EC		Estimated cyan				
		Int. cancellation			AT	LT
		PB + AT	PB + LT	EM		
L	S	95.56	95.56	95.56	95.56	95.56
	D	100	100	83.72	90.70	100
M	S	93.33	93.33	93.33	93.33	93.33
	D	100	100	85.71	92.86	100
Q	S	95.56	95.56	95.56	95.56	95.56
	D	97.67	100	88.37	95.35	100
H	S	95.56	95.56	95.56	95.56	95.56
	D	100	100	90.70	100	100

- Similar performance observed for Aztec codes

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Conclusions

- A methodology to generalize monochrome barcodes to color
  - Utilizes built-in components from monochrome counterpart: localization, data encoding/extraction, error recovery
- Provides higher rate per unit area (x3)
- Enables greater versatility in Mobile connectivity to print
  - Advertisement monetization, multiple
- Methodology generalizes to other barcodes ….

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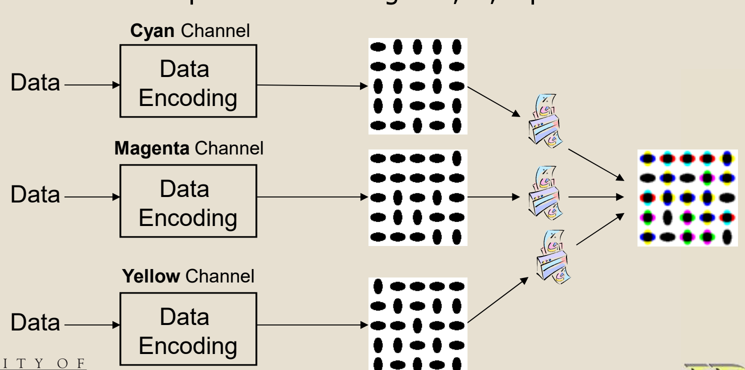
A High Capacity Barcode: Independent Per-Colorant Channel Data Encoding[Bulan2009]

- Data Encoding In Periodic Arrays of Elliptical Dots
  - Orientation encodes data
  - Self-synchronizing (global and local) [Bulan2010,Bulan2011b]
  - 3 X Data: Independent encoding in C, M, Y print colorants



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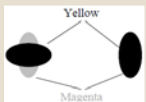
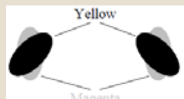
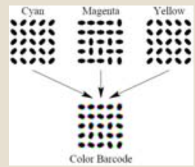
Prior Work: Color Interference Management[Bulan2011b]

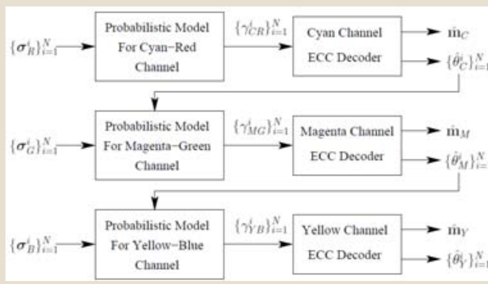
- Encoder: Symmetric constellations for most interfering colorants



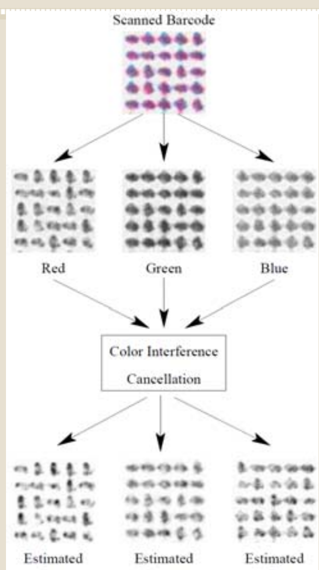




- Decoder: Sequential, interference aware



EM Based Interference Cancellation for Orientation Modulation Barcodes



Experimental Results

- BER in color channels with and without interference cancellation

	Estimated Cyan	Estimated Magenta	Estimated Yellow
Without Int. Cancellation	0.10	0.03	0.28
Proposed EM-style Cancellation	0.10	0	0.10

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Experimental Results

- Error-free rates of the proposed method
  - LDPC codes

	HP Color 4700	Xerox iGen3	Xerox DocuColor 8000
75lpi	1757	1898	1898
100lpi	2812	3000	3333

- Storage rates for the existing barcode technologies

Technique	Storage Capacity Byte/Inch sq.
DataMatrix	1555
Aztec Code	1888
QR Code	1941
Microsoft Color Barcodes	2188
Multilevel 2D Barcodes	2397

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Questions?

References

- US Patent # 9111186, "Color barcodes for mobile applications: A per channel framework," issued 18 Aug. 2015, Inventors: H. Blasinski, O. Bulan, and G. Sharma, Assignee: University of Rochester
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H. Blasinski, O. Bulan, and G. Sharma, "Color barcodes for mobile applications: A per channel framework," *IEEE Trans. Image Processing*, vol. 22, no. 4, Apr. 2013, pp. 1498-1511.

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Demo

Robust Color QR Codes for Added Versatility in Mobile to Print Connectivity

- Immediacy is key in mobile applications (reducing clicks)
- Advertisement monetization
- Win-win-win
  - Consumer (privacy and transparency)
  - Advertiser (advertisement tracking, localization, cross-promotion with social media)
  - Print provider (piggybacked publicity, drawing traffic to web through print)

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