

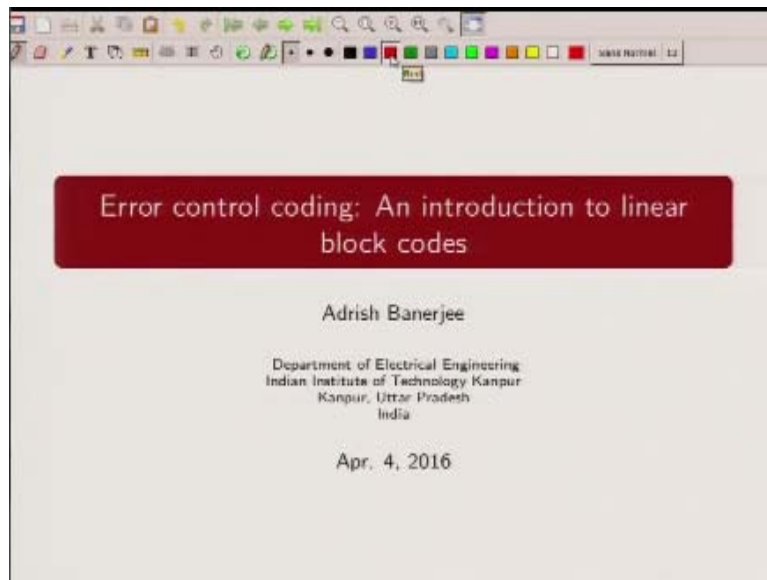
Indian Institute of Technology Kanpur
National Programme on Technology Enhanced Learning (NPTEL)
Course Title
Error Control Coding: An Introduction to Linear Block Codes

Lecture -10
Applications of Linear Block Codes

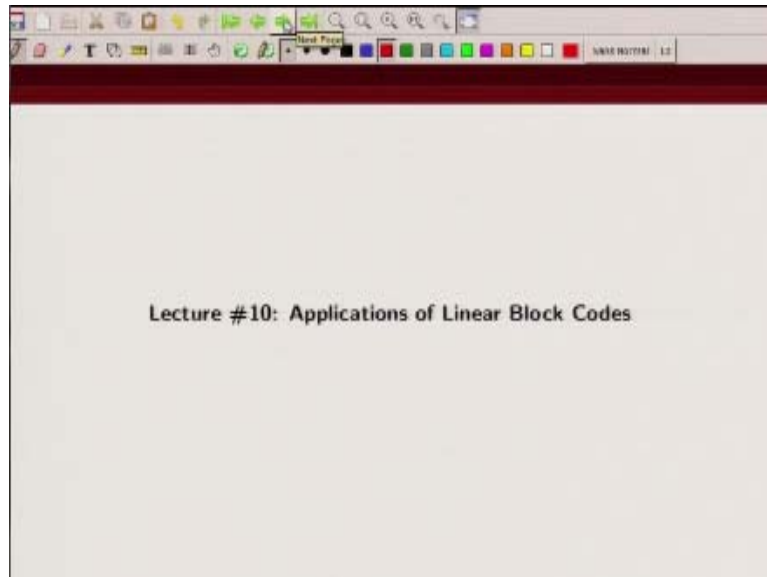
by
Prof. Adrish Banerjee
Department of Electrical Engineering, IIT Kanpur

Welcome to the course on error control coding, an introduction to linear block codes.

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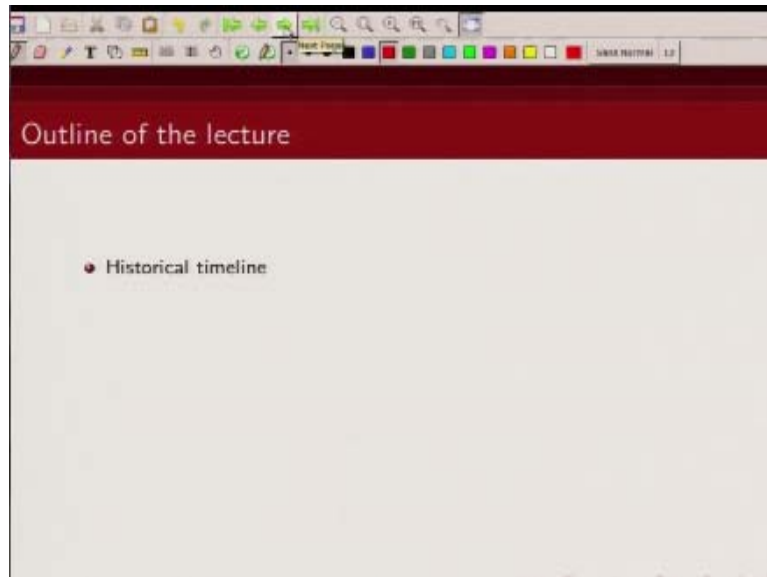


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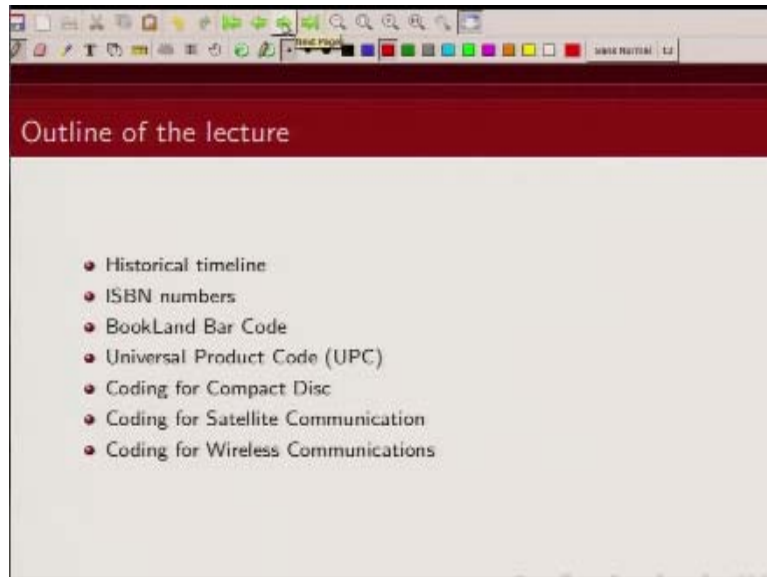
In this lecture we are going to talk about some of the applications of linear block codes.

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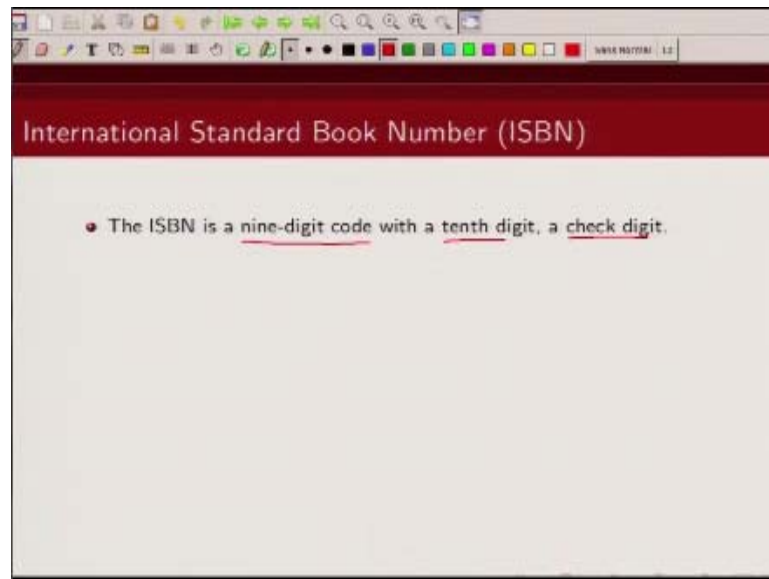
So we will first start with a brief historical timeline of how coding theory has progressed over years.

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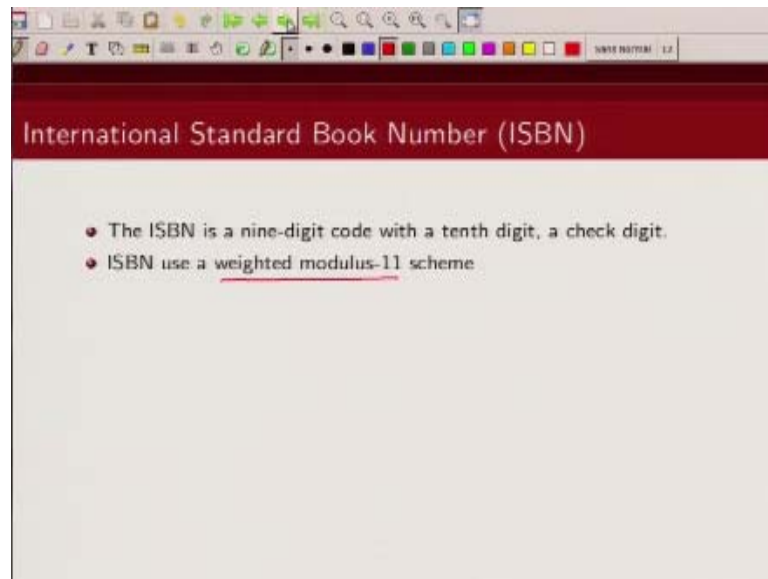
Then we will start with some basic examples, we start off with ISBN number and BookLand bar code. Then we will talk about Universal Product Code and European article number. Then we will talk about some of the applications of error control coding in practice. So we will start off with applications in compact disc, then we will talk about applications in satellite communication as well as deep space explorations and finally we will conclude with applications and wireless communications.

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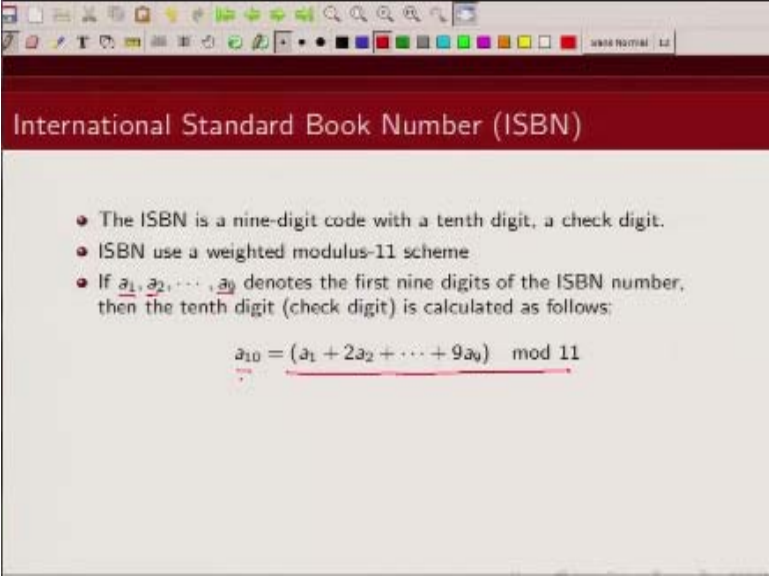
So what is an ISBN number? An ISBN number is a nine digit code with a 10 digit which is a check digit. So it is a 10 digit number, you have a nine digit code plus one bit which is a check bit. So how is this check bit calculated?

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This check bit is calculated as follows. It uses a weighted modulus-11 arithmetic.

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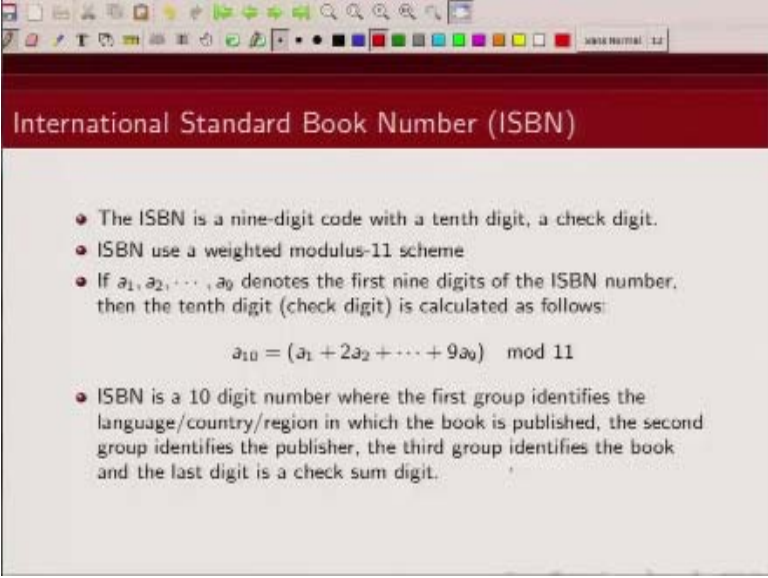
International Standard Book Number (ISBN)

- The ISBN is a nine-digit code with a tenth digit, a check digit.
- ISBN use a weighted modulus-11 scheme
- If $a_1, a_2, \dots, a_9$ denotes the first nine digits of the ISBN number, then the tenth digit (check digit) is calculated as follows:

$$a_{10} = (a_1 + 2a_2 + \dots + 9a_9) \mod 11$$

So let us denote the nine bits of ISBN number by a_1, a_2, a_3 , and a_9 , then the tenth bit is calculated as follows. So $a_1 + 2a_2 + 3a_3 + 4a_4$ up to $9a_9$ modulus-11 will give us the tenth bit. So the tenth bit is actually a check bit.

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International Standard Book Number (ISBN)

- The ISBN is a nine-digit code with a tenth digit, a check digit.
- ISBN use a weighted modulus-11 scheme
- If $a_1, a_2, \dots, a_9$ denotes the first nine digits of the ISBN number, then the tenth digit (check digit) is calculated as follows:
$$a_{10} = (a_1 + 2a_2 + \dots + 9a_9) \mod 11$$
- ISBN is a 10 digit number where the first group identifies the language/country/region in which the book is published, the second group identifies the publisher, the third group identifies the book and the last digit is a check sum digit.

An ISBN is typically a 10 digit number where the first group identifies the country region where the book is published, the second group identifies the publisher and third group identifies the specific book and finally the last bit is actually a check bit. So let us take an example, let us take this book. This is one of our reference book that we are using, The Theory of Error Correcting Codes, by MacWilliams and Slone. So if we look at the ISBN number for this book.

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International Standard Book Number (ISBN)

0 4 4 4 8 5 1 9 3 3
 ↑ ↑ ↑ ↑ ↑ ↑ ↑ ↑ ↑ ↑

- The ISBN is a nine-digit code with a tenth digit, a check digit.
- ISBN use a weighted modulus-11 scheme
- If $a_1, a_2, \dots, a_9$ denotes the first nine digits of the ISBN number, then the tenth digit (check digit) is calculated as follows:

$$a_{10} = (a_1 + 2a_2 + \dots + 9a_9) \bmod 11$$

0 + 2x4 + 3x4 + 4x4 + 5x8 + 6x1 + 7x1 + 8x9 + 9x3 = 102 mod 11 = 3

- ISBN is a 10 digit number where the first group identifies the language/country/region in which the book is published, the second group identifies the publisher, the third group identifies the book and the last digit is a check sum digit.

The ISBN number for this book is 0444851933 okay. So let us check whether – so this is the first bit, second bit, third bit, fourth bit, fifth bit, sixth bit, seventh bit, eighth bit, and this is the ninth bit, and this is our check bit okay. So let us check whether this is correct or not. So how is the check bit calculated? It is a_{10} so a_1 in this case is 0, $2a_2$ that is 4, $3a_3$ that is 4, $4a_4$ which is again 4 plus $5a_5 + 6a_6 + 7a_7 + 8a_8$ and $9a_9$ okay.

And this comes out to be 102, now 102 modulus 11 is, so $11 \times 9 = 99$ so it will be 3 modulo 11. So this 102 modulus 11 is going to be 3 and that is precisely our check bit is, okay. Now the interesting part about these ISBN numbers are that they can detect transposition error.

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International Standard Book Number (ISBN)

- The ISBN is a nine-digit code with a tenth digit, a check digit.
- ISBN use a weighted modulus-11 scheme
- If $a_1, a_2, \dots, a_9$ denotes the first nine digits of the ISBN number, then the tenth digit (check digit) is calculated as follows:

$$a_{10} = (a_1 + 2a_2 + \dots + 9a_9) \bmod 11$$

Handwritten calculation for ISBN 0444851933:

$$0 + 2 \times 4 + 3 \times 4 + 4 \times 4 + 5 \times 8 + 6 \times 5 + 7 \times 1 + 8 \times 9 + 9 \times 3 = 98 \bmod 11 = 10 \rightarrow X$$

Handwritten calculation for ISBN 4044851933:

$$4 + 2 \times 0 + 3 \times 4 + 4 \times 4 + 5 \times 8 + 6 \times 5 + 7 \times 1 + 8 \times 9 + 9 \times 3 = 98 \bmod 11 = 10 \rightarrow X$$

So what is the transposition error? So let us say when you are reading this ISBN number with a bar code reader the most common mistake that happens is the adjacent bits are read wrongly. So for example this is 0444851933, if it is read like 4044851933 that means these two bits are changed, this is transposition error. Then this particular code can detect such errors, we can verify this, let us say this is the number which is being read by the bar code reader.

We try to find out the check bit in this case, so this would be the difference would be here it is these two things will be changed, because these two bits got, so it will be $4 + 2 \times 0$ and that would be 98. So this will be $98 \bmod 11$ and what is $98 \bmod 11$, $11 \times 8 = 88$ so that is 10, so that would be X. Note that this check bit is not matching with the check bit calculated this way. So you can see this particular ISBN code can detect transposition error.

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International Standard Book Number (ISBN)

- The ISBN is a nine-digit code with a tenth digit, a check digit.
- ISBN use a weighted modulus-11 scheme
- If $a_1, a_2, \dots, a_9$ denotes the first nine digits of the ISBN number, then the tenth digit (check digit) is calculated as follows:

$$a_{10} = (a_1 + 2a_2 + \dots + 9a_9) \mod 11$$

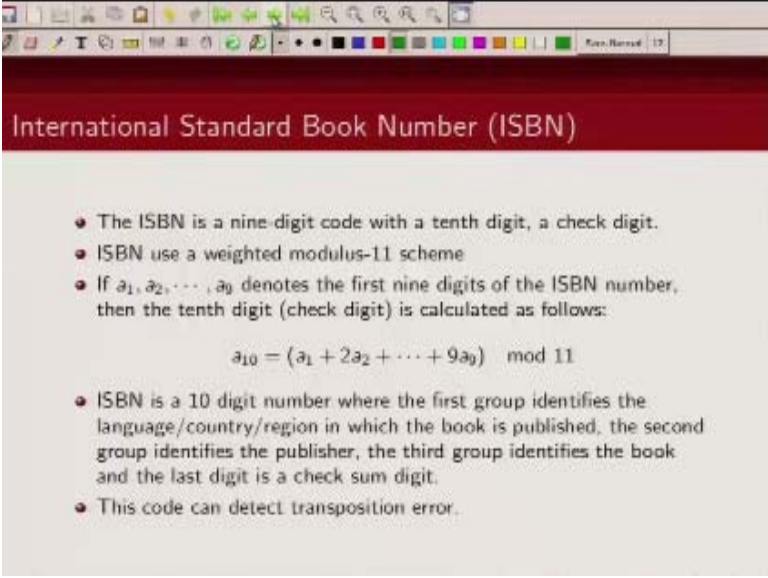
Handwritten calculation for ISBN 0444851933:

$0 \times 1 + 4 \times 2 + 4 \times 3 + 4 \times 4 + 8 \times 5 + 1 \times 6 + 9 \times 7 + 3 \times 8 = 98 \mod 11 = 0$

Handwritten note: "The correct number was 0444851933 and these two bits got interchanged, transposition error happened and you can see using this ISBN number we are able to detect such errors."

The correct number was 0444851933 and these two bits got interchanged, transposition error happened and you can see using this ISBN number we are able to detect such errors.

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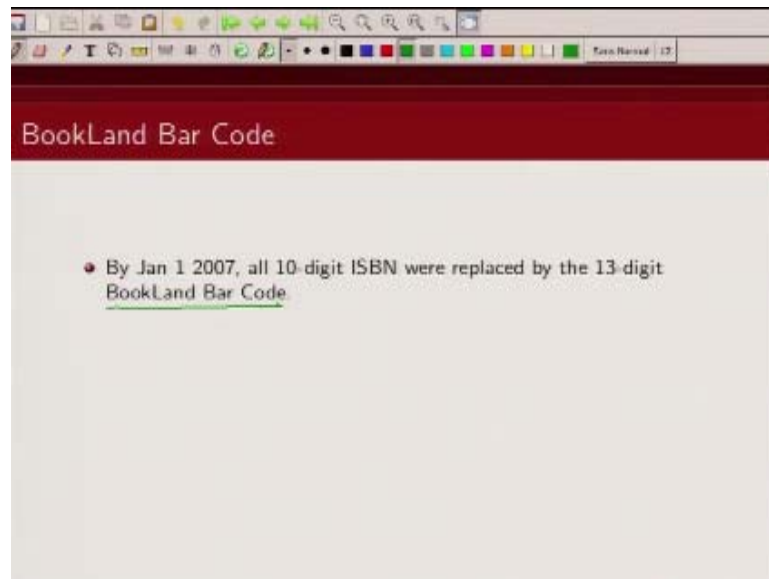


International Standard Book Number (ISBN)

- The ISBN is a nine-digit code with a tenth digit, a check digit.
- ISBN use a weighted modulus-11 scheme
- If $a_1, a_2, \dots, a_9$ denotes the first nine digits of the ISBN number, then the tenth digit (check digit) is calculated as follows:
$$a_{10} = (a_1 + 2a_2 + \dots + 9a_9) \mod 11$$
- ISBN is a 10 digit number where the first group identifies the language/country/region in which the book is published, the second group identifies the publisher, the third group identifies the book and the last digit is a check sum digit.
- This code can detect transposition error.

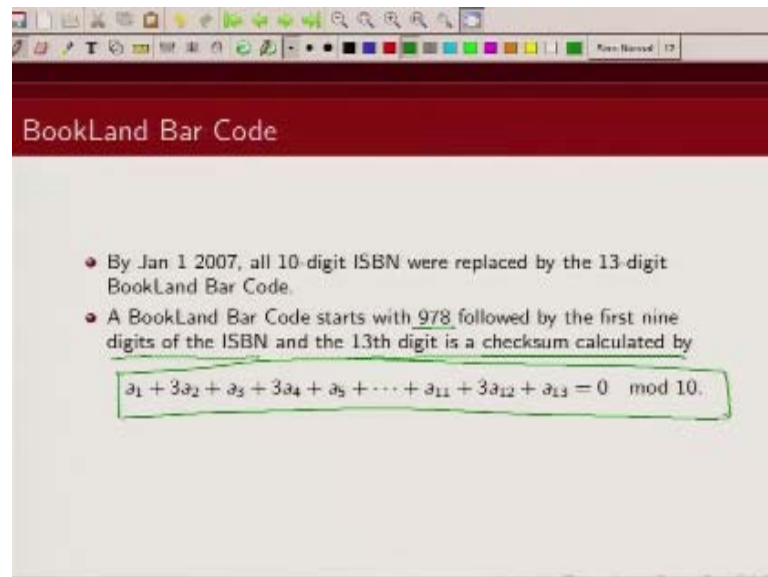
Okay.

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Now by 2007 all these ISBN numbers were replaced by this 13 digit BookLand Bar Code number and what are these BookLand Bar Code numbers?

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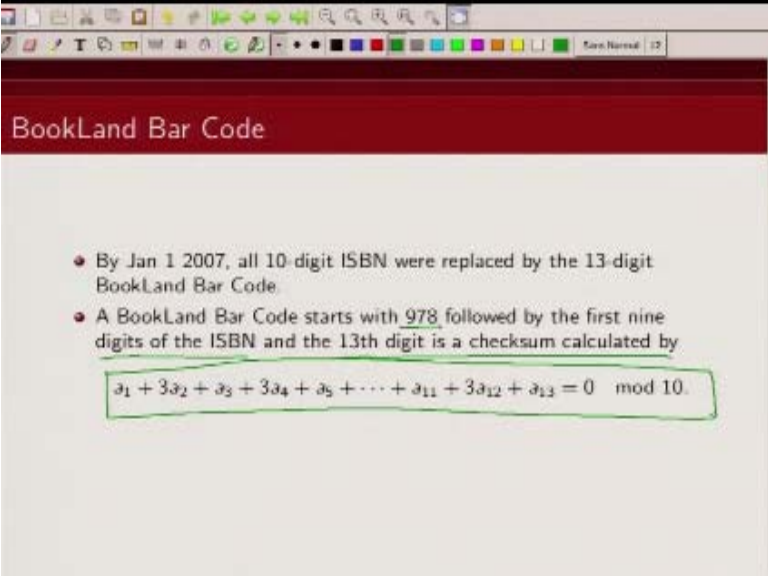
BookLand Bar Code

- By Jan 1 2007, all 10-digit ISBN were replaced by the 13-digit BookLand Bar Code.
- A BookLand Bar Code starts with 978 followed by the first nine digits of the ISBN and the 13th digit is a checksum calculated by

$$a_1 + 3a_2 + a_3 + 3a_4 + a_5 + \dots + a_{11} + 3a_{12} + a_{13} = 0 \pmod{10}$$

So a BookLand Bar Code number starts with 978 and then it is followed by nine digits of ISBN number and the 13th bit is a check sum which is calculated in this particular way okay. This is how we are computing the 13th bit which is the check sum bit.

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The image is a screenshot of a presentation slide. At the top, there is a red header bar with the text "BookLand Bar Code" in white. Below the header, the slide has a light gray background. There are two bullet points: the first says "By Jan 1 2007, all 10- digit ISBN were replaced by the 13-digit BookLand Bar Code." and the second says "A BookLand Bar Code starts with 978 followed by the first nine digits of the ISBN and the 13th digit is a checksum calculated by". Below the second bullet point, a green rectangular box contains the mathematical formula:
$$a_1 + 3a_2 + a_3 + 3a_4 + a_5 + \dots + a_{11} + 3a_{12} + a_{13} = 0 \pmod{10}.$$

Now let us look at an example, so let us consider our book. This error control coding by Lynn Costello and what is its BookLand Bar Code number?

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BookLand Bar Code

978-81-317-3440-7
 $a_1 a_2 a_3 a_4 a_5 a_6 a_7 a_8 a_9 a_{10} a_{11} a_{12} a_{13}$

- By Jan 1 2007, all 10-digit ISBN were replaced by the 13-digit BookLand Bar Code.
- A BookLand Bar Code starts with 978 followed by the first nine digits of the ISBN and the 13th digit is a checksum calculated by

$$a_1 + 3a_2 + a_3 + 3a_4 + a_5 + \dots + a_{11} + 3a_{12} + a_{13} = 0 \pmod{10}$$

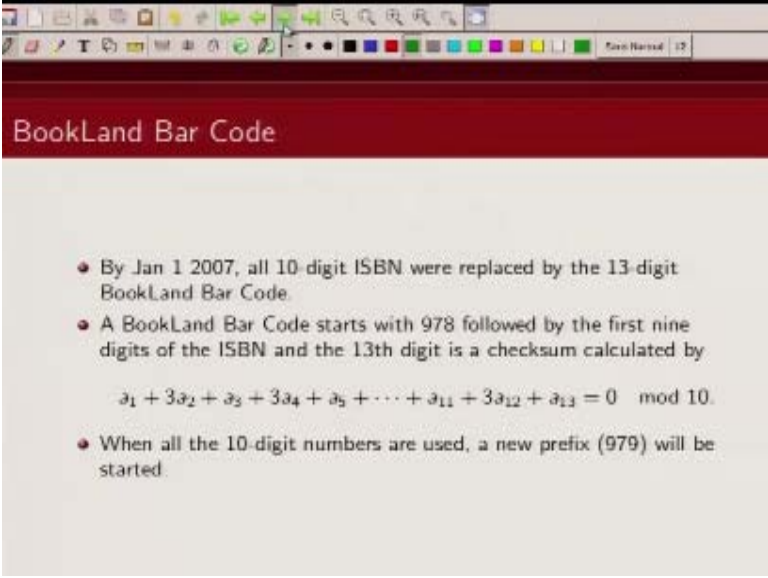
$$(9+8+1+1+3+4+7) + 3 \times (7+8+3+7+4+0) = 120 \pmod{10} = 0$$

That is given by 978-81-317-3440-7 so this is the 13 bit digit number which is given by – which is the ISBN number 13 digit BookLand Bar Code number of this text book that we are using. Now so this is my a_1 , this is my a_2 , this is a_3 , this is my a_4 , a_5 , this is a_6 , a_7 , a_8 , a_9 , this is a_{10} , this is a_{11} , this is a_{12} , and this is a_{13} . So let us look at whether we are getting the same check bit as plotted by this.

So let us – so you can see here what we are doing is, all odd digit numbers we are adding them up right. And all even numbers we are adding them up and multiplying them by 3. So this would be then 9+ -- let me first take all the odd bit numbers. Odd bit numbers are this, the ones I am marking by, these are my odd locations right. So this is $(9+8+1+1+3+4+7)+3$ times the even numbers, even numbers are this $(7, 8, 3, 7, 4, 0)$ so this is $(7+8+3+7+4+0)$ okay.

And this comes out to be $120 \pmod{10}$ which is 0. So as you can see from this example that this check bit is correct, because a_{13} this should be $0 \pmod{10}$. So this is the example of a BookLand Bar Code. And then all the books now have these 13 digit ISBN number.

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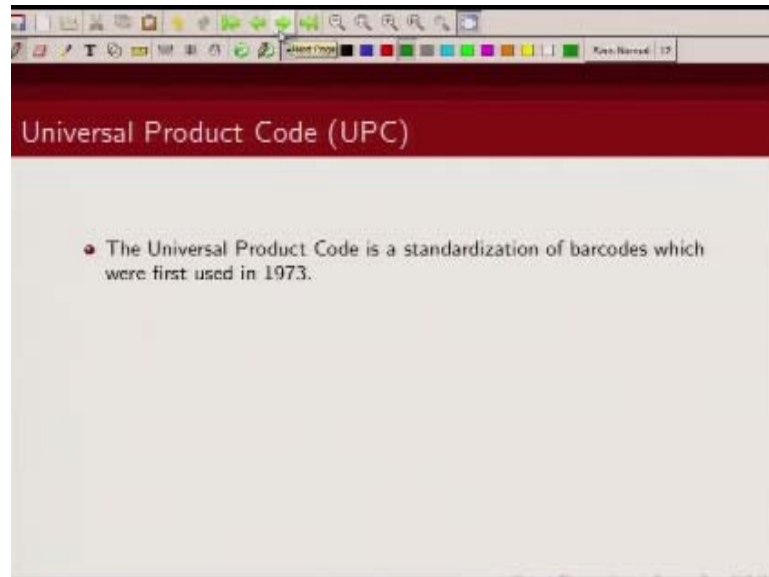


BookLand Bar Code

- By Jan 1 2007, all 10-digit ISBN were replaced by the 13-digit BookLand Bar Code.
- A BookLand Bar Code starts with 978 followed by the first nine digits of the ISBN and the 13th digit is a checksum calculated by
$$a_1 + 3a_2 + a_3 + 3a_4 + a_5 + \dots + a_{11} + 3a_{12} + a_{13} = 0 \pmod{10}.$$
- When all the 10-digit numbers are used, a new prefix (979) will be started.

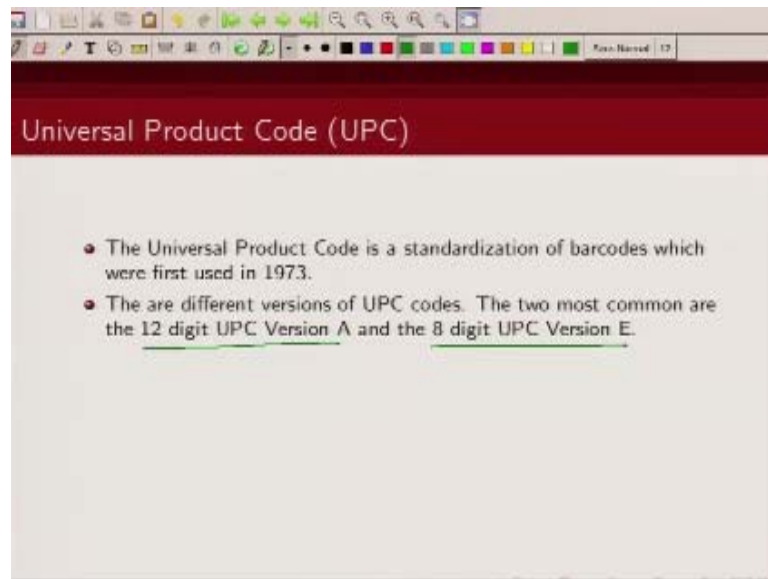
Now once they will get exhausted with this 978 number they will start numbers with 979.

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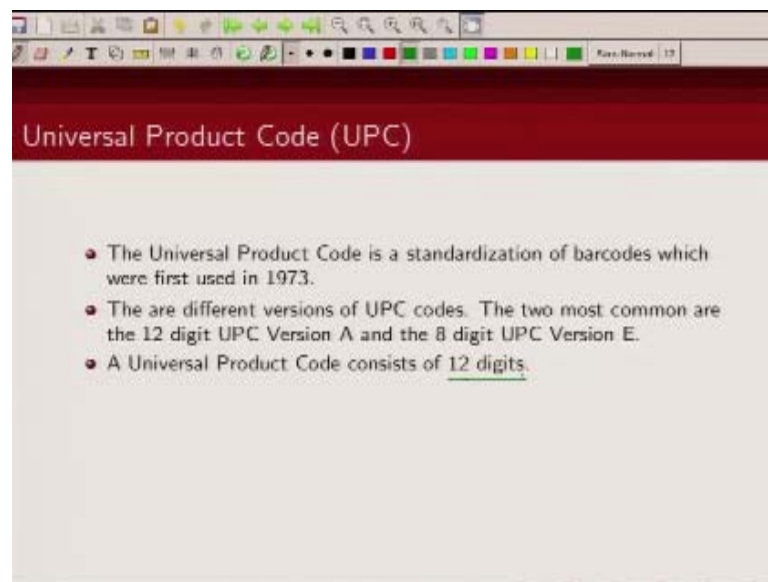
Now next application that we are going to talk about is this Universal Product Code. So this was basically a standardization of all bar codes which was first used in 1973.

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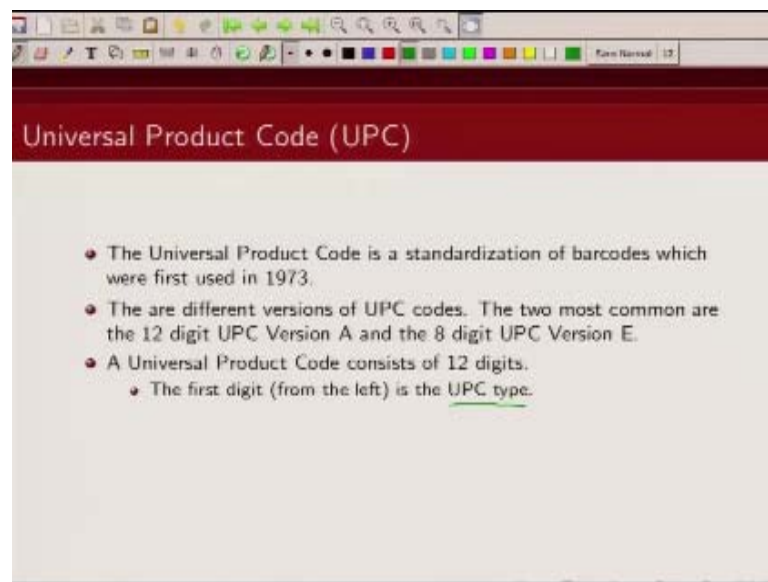
So there are two versions of it, one is this 12 digit UPC version A and the other one is this 8 bit UPC version E.

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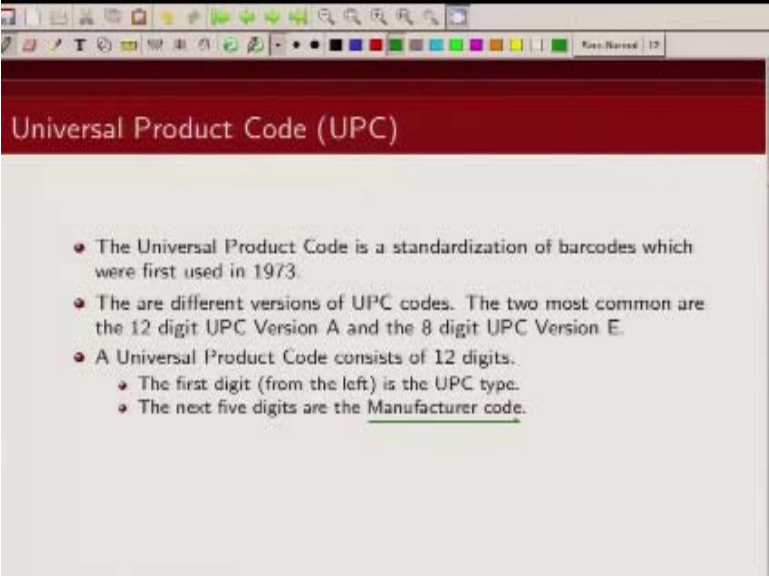
So a 12 digit UPC version has consist of 12 digits.

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The first digit from the left is of UPC type.

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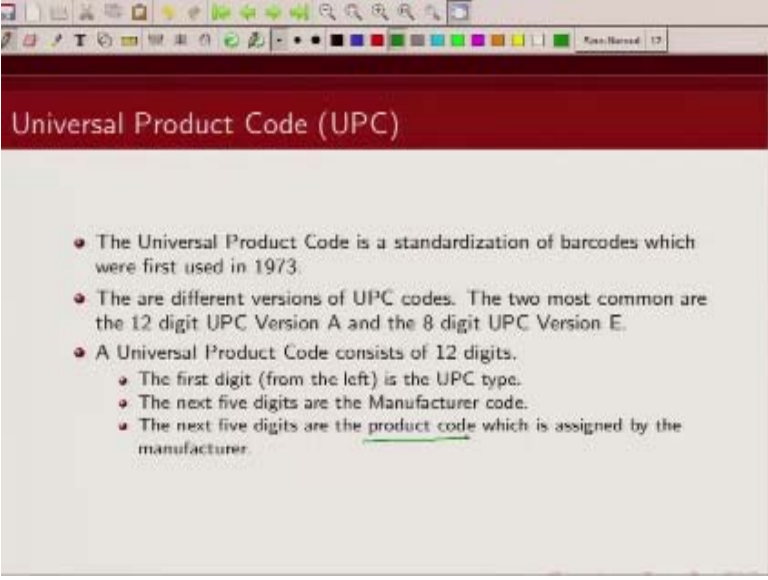
The image is a screenshot of a presentation slide. At the top, there is a dark red header bar with the title "Universal Product Code (UPC)" in white text. Below the header, the slide has a light beige background. A list of bullet points is centered on the slide. The first bullet point states that the UPC is a standardization of barcodes first used in 1973. The second bullet point mentions two common versions: 12-digit Version A and 8-digit Version E. The third bullet point states that a UPC consists of 12 digits, with sub-bullets explaining that the first digit is the UPC type and the next five digits are the Manufacturer code. The slide is displayed within a window that has a standard toolbar at the top and a status bar at the bottom right showing "Page Number | 17".

Universal Product Code (UPC)

- The Universal Product Code is a standardization of barcodes which were first used in 1973.
- There are different versions of UPC codes. The two most common are the 12 digit UPC Version A and the 8 digit UPC Version E.
- A Universal Product Code consists of 12 digits.
 - The first digit (from the left) is the UPC type.
 - The next five digits are the Manufacturer code.

Next five digits are manufactured code.

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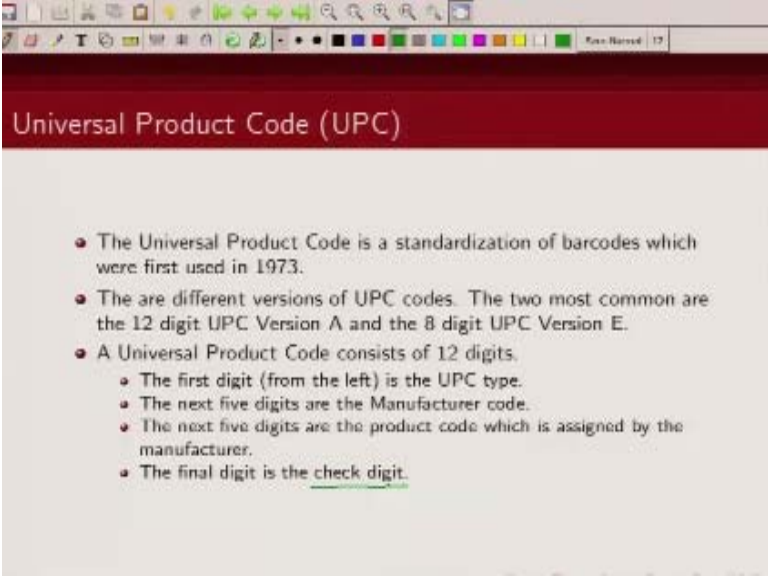
The image shows a presentation slide with a red header bar containing the title 'Universal Product Code (UPC)'. Below the header, the slide content is on a light gray background. It features a bulleted list of facts about UPC codes. The list includes the year of first use (1973), common versions (12-digit and 8-digit), and the structure of a 12-digit code (type, manufacturer, and product code). The word 'product' in the last bullet point is underlined in green. The slide is displayed within a software window with a standard toolbar at the top.

Universal Product Code (UPC)

- The Universal Product Code is a standardization of barcodes which were first used in 1973.
- There are different versions of UPC codes. The two most common are the 12 digit UPC Version A and the 8 digit UPC Version E.
- A Universal Product Code consists of 12 digits.
 - The first digit (from the left) is the UPC type.
 - The next five digits are the Manufacturer code.
 - The next five digits are the product code which is assigned by the manufacturer.

The next five digits are actually the product codes which are assigned by the manufacture.

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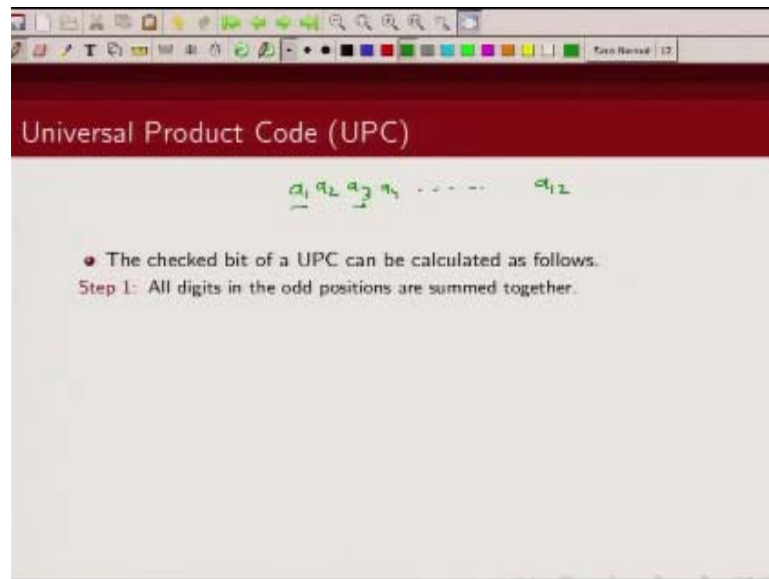


The image is a screenshot of a presentation slide. At the top, there is a dark red header bar with the title "Universal Product Code (UPC)" in white text. Below the header, the slide has a light gray background. A list of bullet points is displayed, explaining the basics of UPC. The list includes the history of the code, common versions, and the structure of a 12-digit code. The final bullet point, which describes the check digit, has the words "check digit" underlined in green.

- The Universal Product Code is a standardization of barcodes which were first used in 1973.
- There are different versions of UPC codes. The two most common are the 12 digit UPC Version A and the 8 digit UPC Version E.
- A Universal Product Code consists of 12 digits.
 - The first digit (from the left) is the UPC type.
 - The next five digits are the Manufacturer code.
 - The next five digits are the product code which is assigned by the manufacturer.
 - The final digit is the check digit.

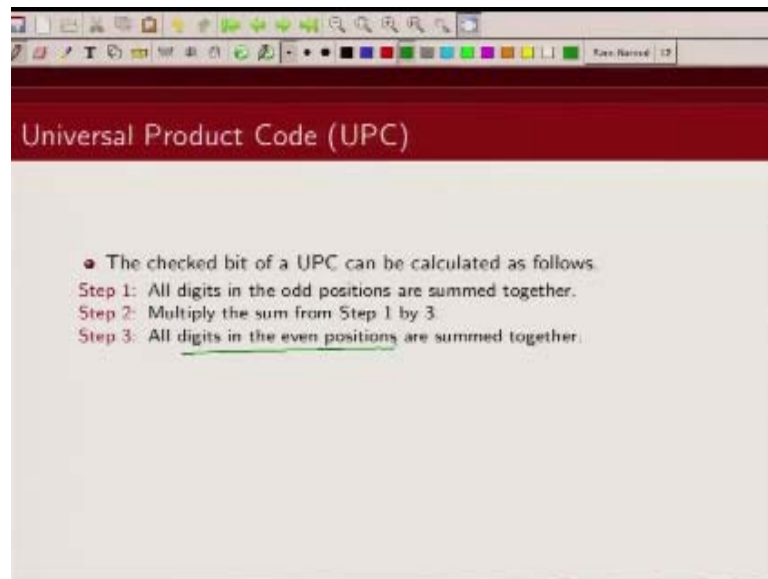
And the final digit is the check bit. So that is what we are going to use for error detection. So how is this check bit computed?

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So this check bit is computed as follows. All digits in the odd positions are summed up. So you have this UPC number which is like a_1, a_2, a_3, a_4 up to a_{12} , then what you are going to do is you are going to add up all the odd numbers in the odd location it is a_1, a_3, a_5 like that.

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And multiply the sum by 3, so you are going to multiply the sum of the odd numbers at the odd location by 3, and to that you are going to add all the digits in the even position. So it will be three times $a_1 + a_3 + a_5$ and $+ a_2 + a_4 + a_6$ like that. So you are going to add the number, so essentially you are weighing the numbers multiplying by 3, 1, 3, 1, like that.

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Universal Product Code (UPC)

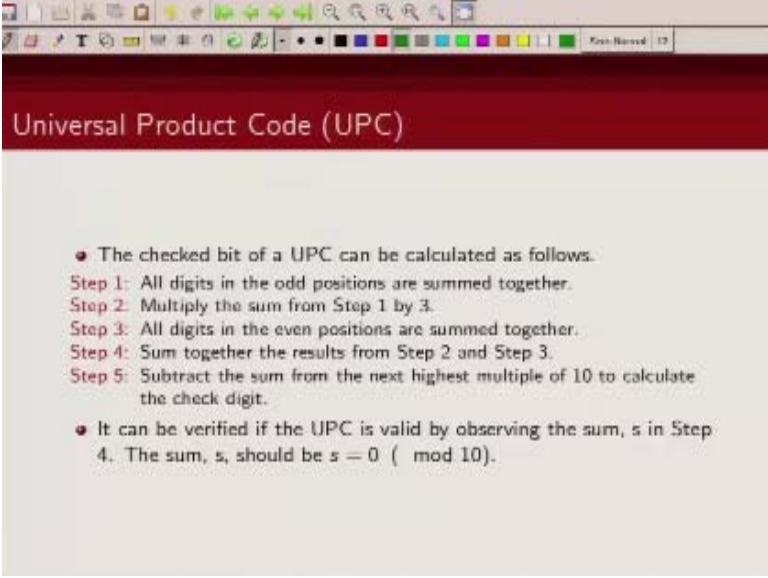
$$3(a_1 + a_3 + a_5 + a_7 + a_{11}) + (a_2 + a_4 + \dots + a_{10}) + a_{12} = 0 \pmod{10}$$

- The checked bit of a UPC can be calculated as follows.
- Step 1: All digits in the odd positions are summed together.
- Step 2: Multiply the sum from Step 1 by 3.
- Step 3: All digits in the even positions are summed together.
- Step 4: Sum together the results from Step 2 and Step 3.
- Step 5: Subtract the sum from the next highest multiple of 10 to calculate the check digit.

And you are going to add them all up and subtract the sum that you get from the next highest multiple of 10. So what I am saying is, so you have this $3(a_1 + a_3 + a_5 + a_7 + a_{11}) +$ you have this $(a_2 + a_4 + \dots)$ you have these when you add them all up plus your 12 bit number, this is your – that should add up to 0 modulo 10 okay. So the odd bit numbers are multiplied by 3, even bit numbers are just added up.

If you add those 11 bits, then the 12th bit which is the check bit should be such that sum of this weighted sum should be 0 modulo 10.

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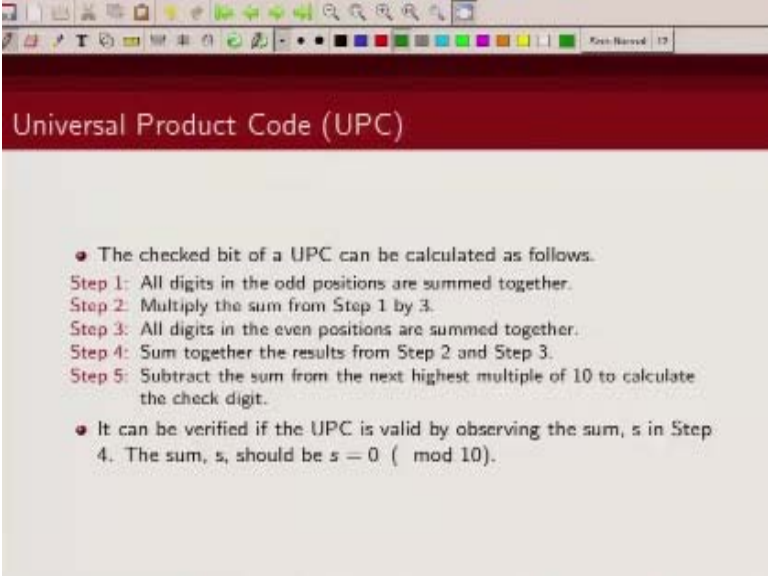
The image shows a presentation slide with a dark red header containing the title "Universal Product Code (UPC)". Below the header, the slide contains a bulleted list of steps for calculating the check digit of a UPC. The steps are numbered 1 through 5. A final bullet point states that the sum s should be 0 modulo 10 for a valid UPC. The slide is displayed in a window with a standard toolbar at the top.

Universal Product Code (UPC)

- The checked bit of a UPC can be calculated as follows.
 - Step 1: All digits in the odd positions are summed together.
 - Step 2: Multiply the sum from Step 1 by 3.
 - Step 3: All digits in the even positions are summed together.
 - Step 4: Sum together the results from Step 2 and Step 3.
 - Step 5: Subtract the sum from the next highest multiple of 10 to calculate the check digit.
- It can be verified if the UPC is valid by observing the sum, s in Step 4. The sum, s , should be $s = 0 \pmod{10}$.

And that is your UPC code. So the sum that you should get should be 0 modulo 10, sum of all the 12 bit numbers. So three times $a_1 + a_2 + 3a_3 + a_4$ up to $3a_{11} + a_{12}$ should be zero modulo 10 in case of UPC 12 bit, UPC code.

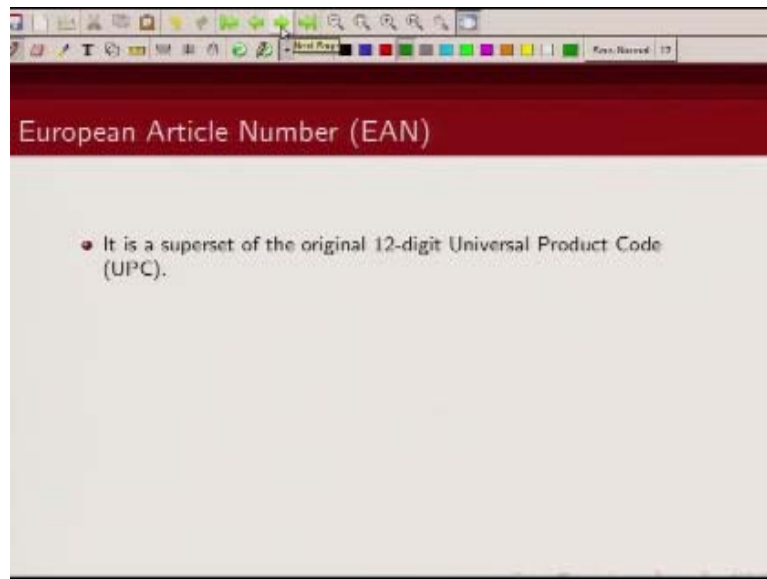
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The slide is titled "Universal Product Code (UPC)" in a dark red header. Below the header, the text is as follows:

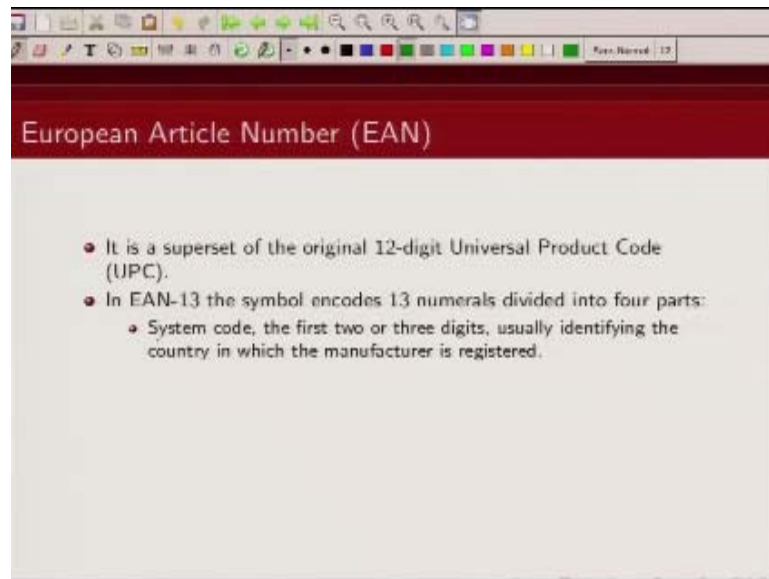
- The checked bit of a UPC can be calculated as follows.
 - Step 1: All digits in the odd positions are summed together.
 - Step 2: Multiply the sum from Step 1 by 3.
 - Step 3: All digits in the even positions are summed together.
 - Step 4: Sum together the results from Step 2 and Step 3.
 - Step 5: Subtract the sum from the next highest multiple of 10 to calculate the check digit.
- It can be verified if the UPC is valid by observing the sum, s in Step 4. The sum, s , should be $s = 0 \pmod{10}$.

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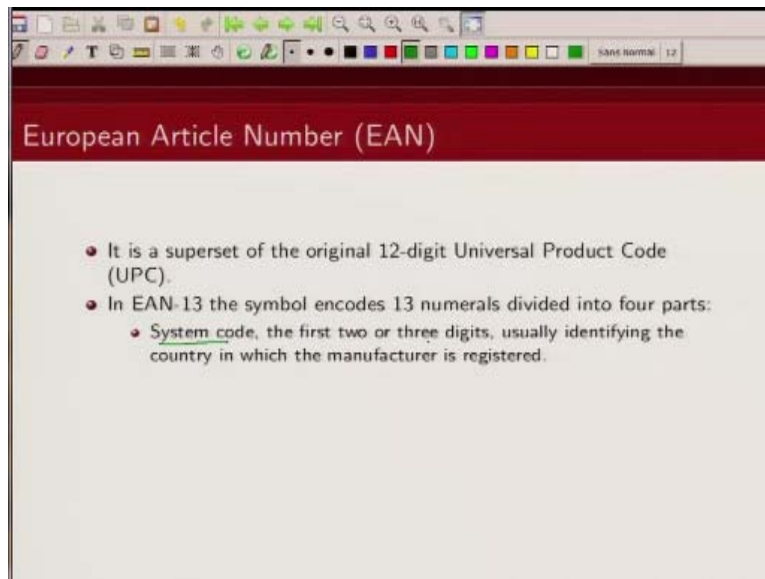
Now a superset of this UPC code 12 bit UPC code is this 13 bit European article number.

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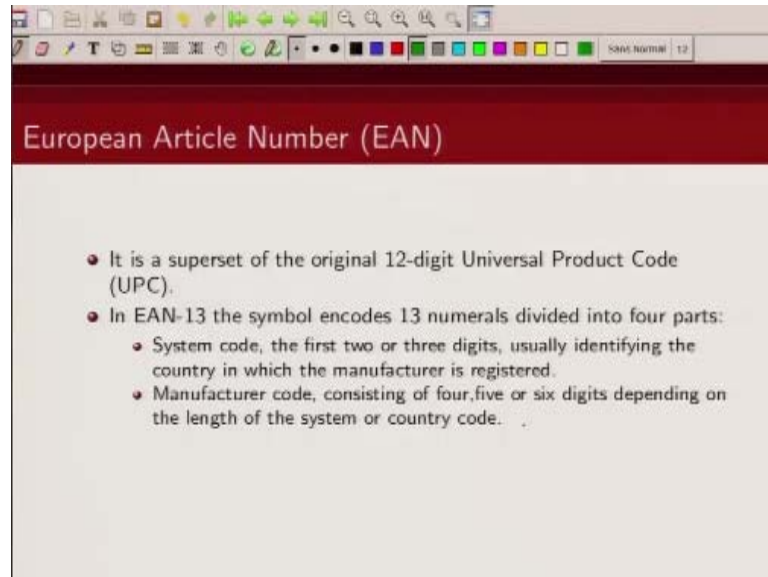
So what is this 13 bit European article number, so it has four parts?

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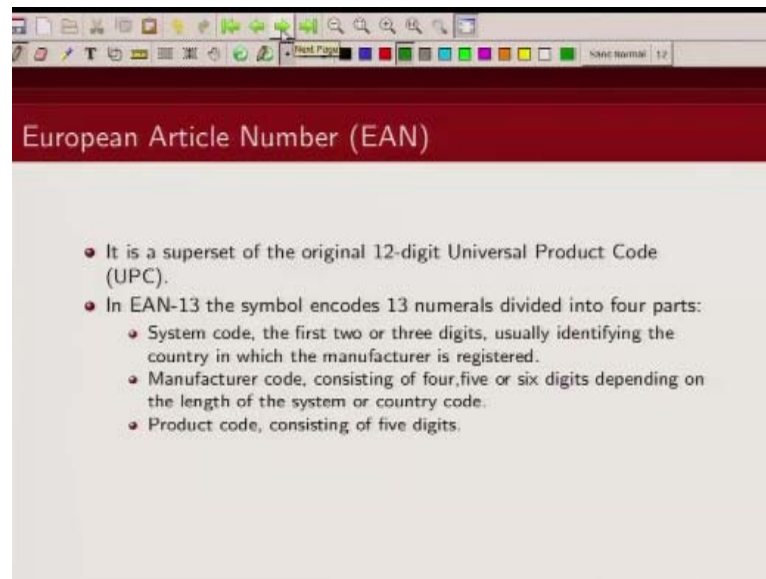
So first is system code which is first two or three bits which identifies a country where the product has been manufactured

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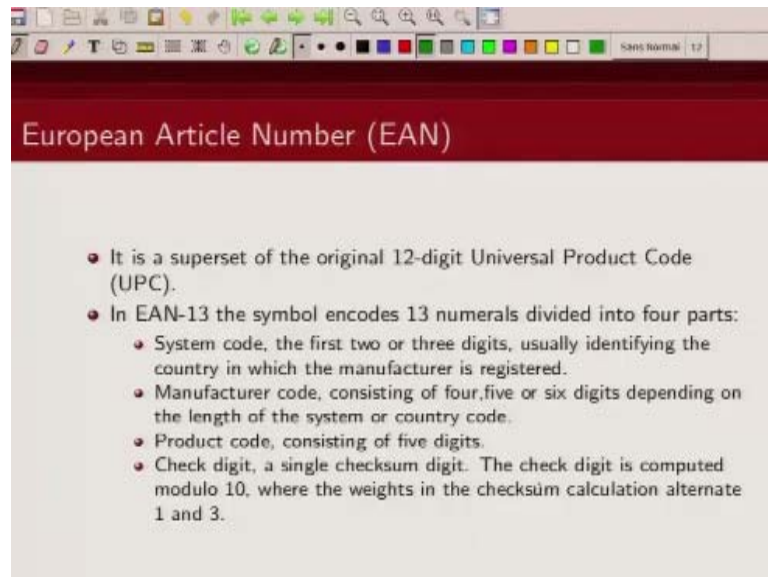
Then you have manufacturer code which is four to six bits

(Refer Slide Time: 15:16)



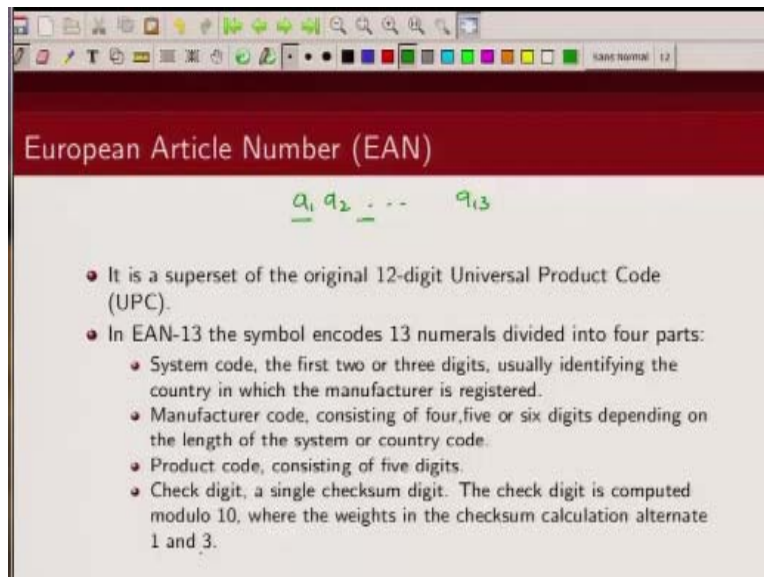
And then you have the product code which consists of five bits

(Refer Slide Time: 15:20)



And finally you have one check bit and this check bit is computed modulo ten where the weights in the checksum calculate, calculation alternate between 1 and 3 now what do I mean by that, so you have this 13 bit number, a_1, a_2, a_{13} , so what you are going to do is these bits in the odd location you multiply by 1 and bits in the even location you multiply by 3, and the modular sum of that should add up to $0 \bmod 10$.

(Refer Slide Time: 15:38)



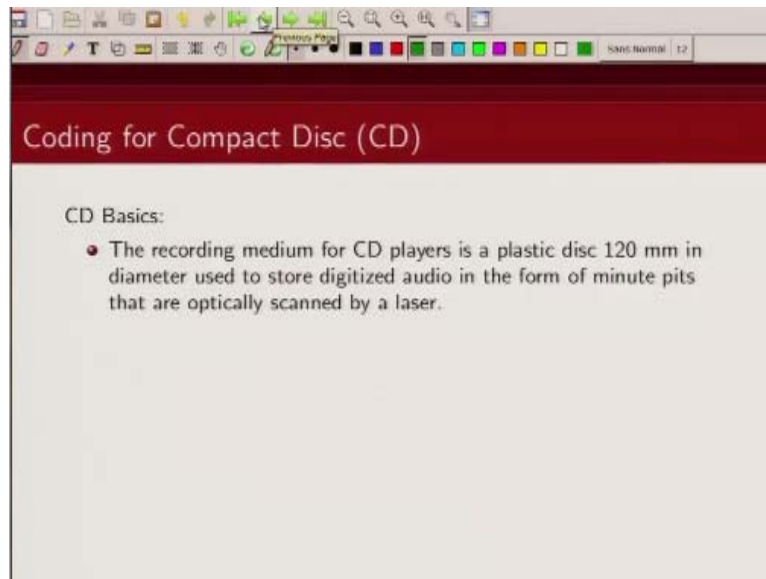
The image is a screenshot of a presentation slide. At the top, there is a dark red header bar with the text "European Article Number (EAN)" in white. Below the header, the slide has a light beige background. In the center, the digits $a_1, a_2, \dots, a_{13}$ are written in green, with each digit underlined. Below this, there is a bulleted list in black text. The first bullet point states that EAN is a superset of the original 12-digit Universal Product Code (UPC). The second bullet point states that in EAN-13, the symbol encodes 13 numerals divided into four parts, followed by four sub-bullets: System code (first two or three digits, identifying the country), Manufacturer code (four, five, or six digits, depending on the system or country code), Product code (five digits), and Check digit (a single checksum digit, computed modulo 10 with alternating weights of 1 and 3).

European Article Number (EAN)

$\underline{a_1} \ \underline{a_2} \ \dots \ \underline{a_{13}}$

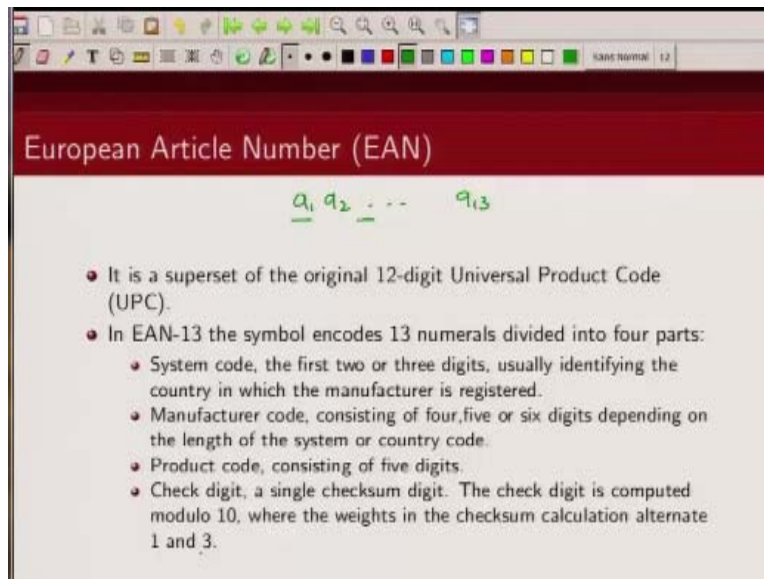
- It is a superset of the original 12-digit Universal Product Code (UPC).
- In EAN-13 the symbol encodes 13 numerals divided into four parts:
 - System code, the first two or three digits, usually identifying the country in which the manufacturer is registered.
 - Manufacturer code, consisting of four, five or six digits depending on the length of the system or country code.
 - Product code, consisting of five digits.
 - Check digit, a single checksum digit. The check digit is computed modulo 10, where the weights in the checksum calculation alternate 1 and 3.

(Refer Slide Time: 16:03)



So let us look at an example to

(Refer Slide Time: 16:07)



The slide is titled "European Article Number (EAN)" in a red header. Below the title, the structure of an EAN-13 code is shown as $a_1 a_2 \dots a_{13}$ in green. The slide contains the following bullet points:

- It is a superset of the original 12-digit Universal Product Code (UPC).
- In EAN-13 the symbol encodes 13 numerals divided into four parts:
 - System code, the first two or three digits, usually identifying the country in which the manufacturer is registered.
 - Manufacturer code, consisting of four, five or six digits depending on the length of the system or country code.
 - Product code, consisting of five digits.
 - Check digit, a single checksum digit. The check digit is computed modulo 10, where the weights in the checksum calculation alternate 1 and 3.

Illustrate that, okay let us look at an example to illustrate that so I have this Britannia bonbon biscuit right and what is this European article number for this,

(Refer Slide Time: 16:23)

The slide is titled "European Article Number (EAN)". It displays the EAN-13 number 8901063139190. Above the digits, positions are labeled: $a_1, a_2, \dots, a_{13}$. The digits are grouped into four parts: 890 (System code), 10631 (Manufacturer code), 391 (Product code), and 90 (Check digit). The check digit '90' is underlined in blue. A list of bullet points explains the structure and checksum calculation. The calculation shows the sum of odd-positioned digits multiplied by 1 and even-positioned digits multiplied by 3, resulting in 120, which modulo 10 equals 0.

European Article Number (EAN)

$a_1, a_2, \dots, a_{13}$
8 9 0 1 0 6 3 1 3 9 1 9 0

- It is a superset of the original 12-digit Universal Product Code (UPC).
- In EAN-13 the symbol encodes 13 numerals divided into four parts:
 - System code, the first two or three digits, usually identifying the country in which the manufacturer is registered.
 - Manufacturer code, consisting of four, five or six digits depending on the length of the system or country code.
 - Product code, consisting of five digits.
 - Check digit, a single checksum digit. The check digit is computed modulo 10, where the weights in the checksum calculation alternate 1 and 3.

$1 \times (8 + 0 + 0 + 3 + 3 + 1 + 0) + 3 \times (9 + 1 + 6 + 1 + 9 + 9) = 120 \pmod{10} = 0$

So European article number for this is 8 9 0 1 0 6 3 1 3 9 1 9 0, so this is my 13 bit, you can see 1,2,3,4,5,6,7,8,10,11,12,13 so these 13 bit European article number. Now let us see whether this checksum bit is correct so what do we need to do, we need to add odd bits and we need to add the even bits, the bits in the even location and multiply them by three, so let us first mark the bits in the odd location, this is 0, 3, 3, 1, 0, okay and what are the bits in the even location, that is marked with this blue pen okay. So let us add up so again the check bit is computed modular ten where weights in the checksum calculation alternate between 1 and 3, so what do I mean by that so every odd bit I multiply by 1 and every even bit I, bits at the even location I multiply by three.

So let me first add up the numbers in the odd location, so that is $8+0+0+3+3+1+0$, this will multiplied by 1 + 3 times numbers in the even location, that is $9+1+6+1+9+9$. 9, 1, 6, 1, 9, 9, and this comes out to be 120 and $120 \pmod{10}$ is 0, so you can see that, that checksum bit is correct. So you can see from the examples that we have done so far the last bit in all these are our check bit which can be used for error deduction.

(Refer Slide Time: 18:17)

The slide is titled "European Article Number (EAN)". It features a handwritten EAN-13 code: 8 9 0 1 0 6 3 1 3 9 1 9 0. Above the digits, the indices $a_1, a_2, \dots, a_{13}$ are written. A green circle highlights the first two digits, 8 and 9. Below the code, a bulleted list explains the structure of EAN-13:

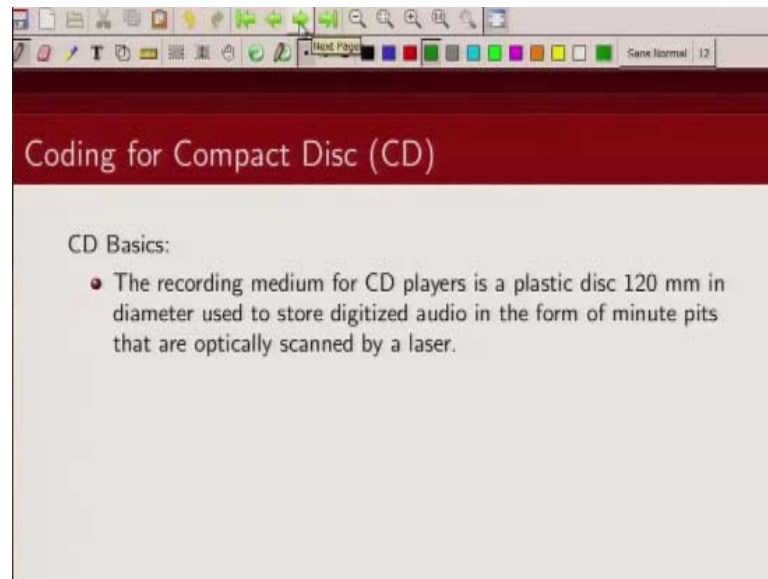
- It is a superset of the original 12-digit Universal Product Code (UPC).
- In EAN-13 the symbol encodes 13 numerals divided into four parts:
 - System code, the first two or three digits, usually identifying the country in which the manufacturer is registered.
 - Manufacturer code, consisting of four, five or six digits depending on the length of the system or country code.
 - Product code, consisting of five digits.
 - Check digit, a single checksum digit. The check digit is computed modulo 10, where the weights in the checksum calculation alternate 1 and 3.

Below the list, the checksum calculation is shown:

$$1 \times (9 + 0 + 0 + 3 + 3 + 1 + 0) + 3 \times (8 + 1 + 6 + 1 + 9 + 9) = 118 \pmod{10} = 8$$

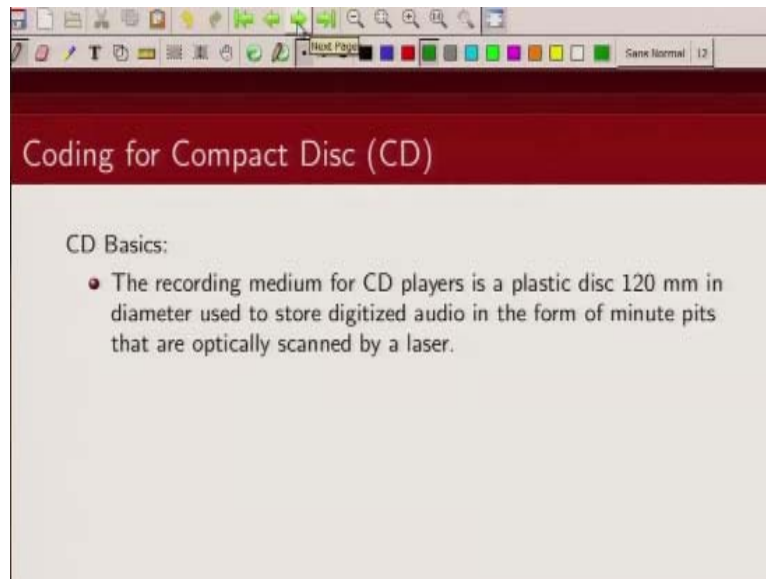
Now this code also can easily find out the transposition error, for example if these two bits would have got exchanged then what would have happened, then here this would have been these things would have changed this would have become 9 and this would have become an 8, so this would have been, this would have changed the sum would have changed so earlier it was 9 times 3, now it is 24 three less and there is one more, so now two less, so this would have become 118 and this is not 0 modulo 10. So you can see this code can correct, can, can detect transposition error and these are the most common error which happen when you are trying to read these bar codes okay. Now let us now move to some other.

(Refer Slide Time: 20:10)



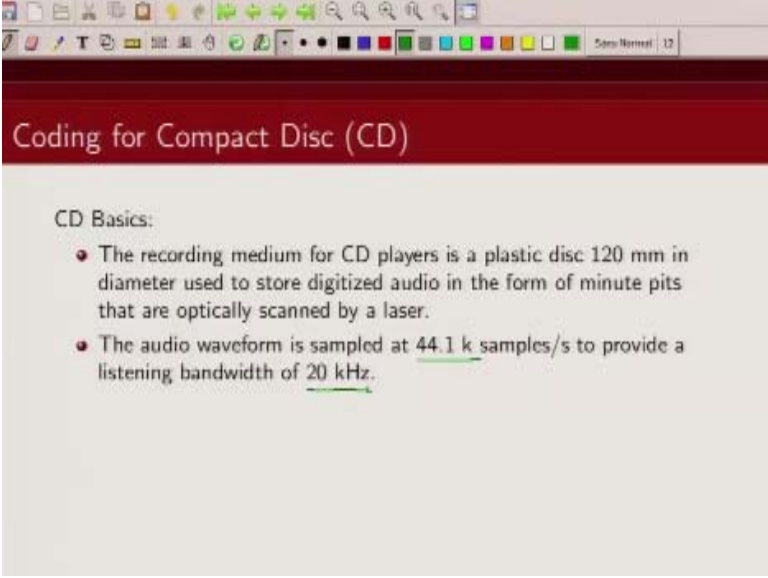
Applications, so we start with application of error control coding in CD's, you are familiar with CD disc, it is basically.

(Refer Slide Time: 20:14)



A plastic disc of 120 mm in diameter and it can be used for storing digital audio, video data

(Refer Slide Time: 20:28)



The image is a screenshot of a presentation slide. At the top, there is a dark red header bar with the title "Coding for Compact Disc (CD)" in white text. Below the header, the slide content is on a light beige background. It starts with the text "CD Basics:" followed by a bulleted list. The first bullet point states: "The recording medium for CD players is a plastic disc 120 mm in diameter used to store digitized audio in the form of minute pits that are optically scanned by a laser." The second bullet point states: "The audio waveform is sampled at 44.1 k samples/s to provide a listening bandwidth of 20 kHz." The text "44.1 k samples/s" and "20 kHz" are underlined in green. The slide is framed by a standard Windows-style window with a toolbar at the top and a status bar at the bottom right showing "Slide Number: 12".

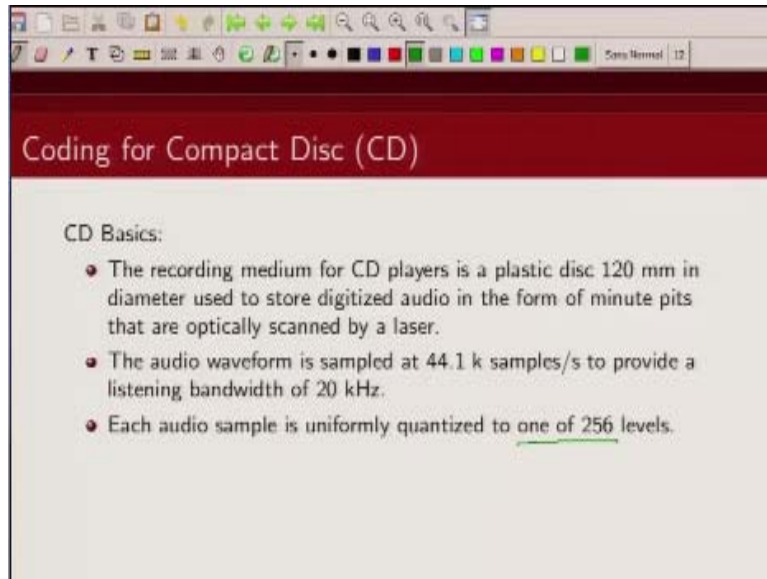
Coding for Compact Disc (CD)

CD Basics:

- The recording medium for CD players is a plastic disc 120 mm in diameter used to store digitized audio in the form of minute pits that are optically scanned by a laser.
- The audio waveform is sampled at 44.1 k samples/s to provide a listening bandwidth of 20 kHz.

Now the audio signal is sampled at 41.1 k samples/s and it provides a listening bandwidth of 20 kHz.

(Refer Slide Time: 20:40)



The image is a screenshot of a presentation slide. At the top, there is a dark red header bar with the title "Coding for Compact Disc (CD)" in white text. Below the header, the slide content is on a light beige background. It starts with the text "CD Basics:" followed by a bulleted list of three points. The third point, "Each audio sample is uniformly quantized to one of 256 levels," has the phrase "one of 256 levels" underlined in green. The slide is displayed within a window that has a standard Windows-style toolbar at the top with various icons for navigation and editing.

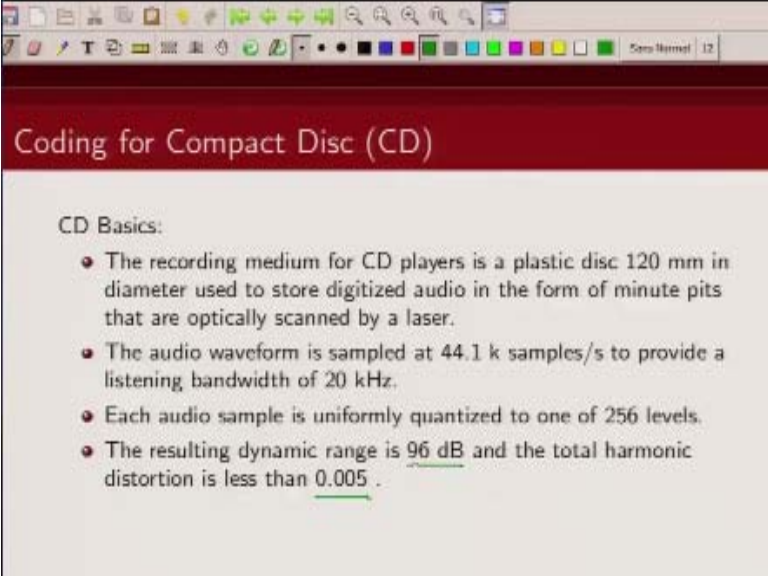
Coding for Compact Disc (CD)

CD Basics:

- The recording medium for CD players is a plastic disc 120 mm in diameter used to store digitized audio in the form of minute pits that are optically scanned by a laser.
- The audio waveform is sampled at 44.1 k samples/s to provide a listening bandwidth of 20 kHz.
- Each audio sample is uniformly quantized to one of 256 levels.

Each audio sample is sample to quantized to one of the 256 levels

(Refer Slide Time: 20:50)



The image is a screenshot of a presentation slide. At the top, there is a dark red header bar with the title "Coding for Compact Disc (CD)" in white text. Below the header, the slide content is on a light beige background. It starts with the heading "CD Basics:" followed by a bulleted list of four points. The list describes the physical properties of a CD, the sampling rate (44.1 k samples/s), the quantization levels (256), and the dynamic range (96 dB) and harmonic distortion (less than 0.005). The numbers 96 dB and 0.005 are underlined in the original image.

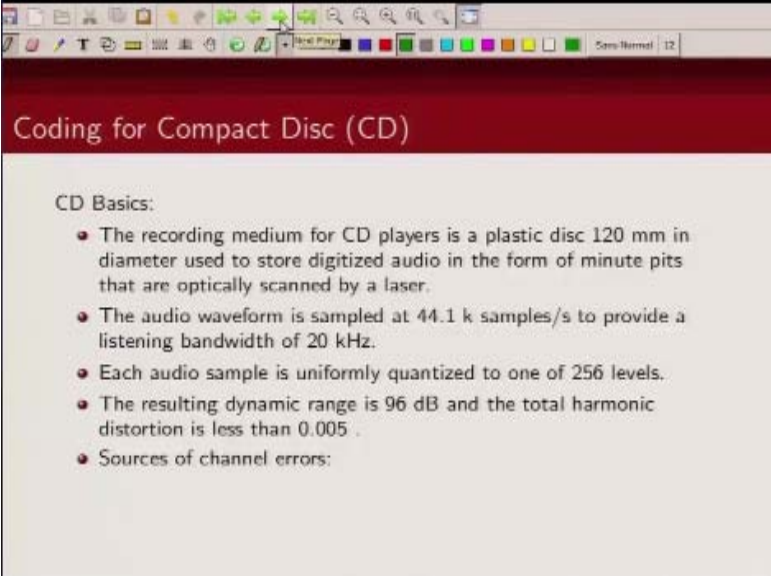
Coding for Compact Disc (CD)

CD Basics:

- The recording medium for CD players is a plastic disc 120 mm in diameter used to store digitized audio in the form of minute pits that are optically scanned by a laser.
- The audio waveform is sampled at 44.1 k samples/s to provide a listening bandwidth of 20 kHz.
- Each audio sample is uniformly quantized to one of 256 levels.
- The resulting dynamic range is 96 dB and the total harmonic distortion is less than 0.005.

Which provides a dynamic range of 96dB and harmonic distortion of less than .005

(Refer Slide Time: 20:59)



The image is a screenshot of a presentation slide. At the top, there is a red header bar with the title "Coding for Compact Disc (CD)" in white text. Below the header, the slide content is on a light beige background. It starts with the section "CD Basics:" followed by a bulleted list of five points. The first point describes the physical disc, the second the sampling rate and bandwidth, the third the quantization levels, the fourth the dynamic range and distortion, and the fifth mentions sources of channel errors. The slide is displayed within a window that has a standard toolbar at the top.

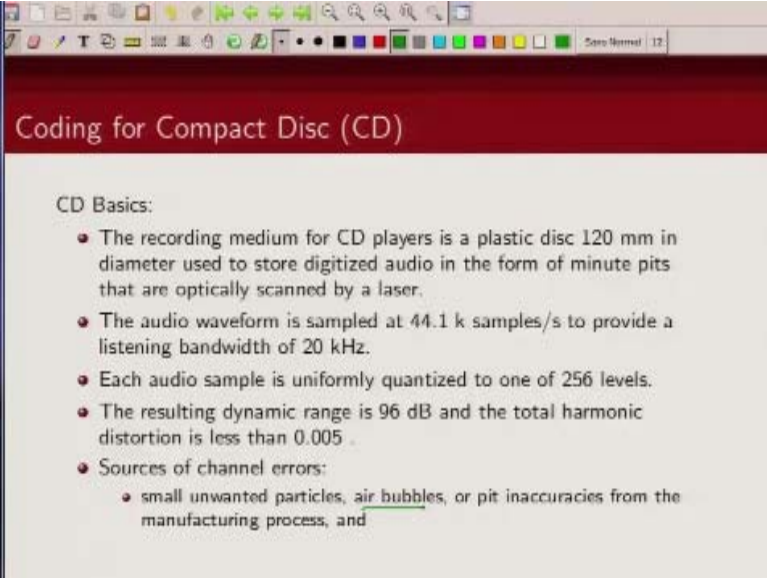
Coding for Compact Disc (CD)

CD Basics:

- The recording medium for CD players is a plastic disc 120 mm in diameter used to store digitized audio in the form of minute pits that are optically scanned by a laser.
- The audio waveform is sampled at 44.1 k samples/s to provide a listening bandwidth of 20 kHz.
- Each audio sample is uniformly quantized to one of 256 levels.
- The resulting dynamic range is 96 dB and the total harmonic distortion is less than 0.005 .
- Sources of channel errors:

Now what are the sources of error in a CD disc?

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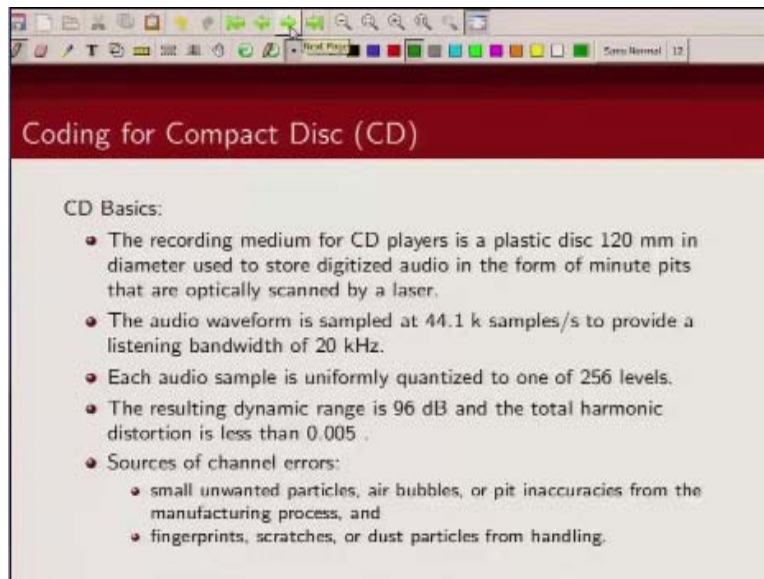
Coding for Compact Disc (CD)

CD Basics:

- The recording medium for CD players is a plastic disc 120 mm in diameter used to store digitized audio in the form of minute pits that are optically scanned by a laser.
- The audio waveform is sampled at 44.1 k samples/s to provide a listening bandwidth of 20 kHz.
- Each audio sample is uniformly quantized to one of 256 levels.
- The resulting dynamic range is 96 dB and the total harmonic distortion is less than 0.005 .
- Sources of channel errors:
 - small unwanted particles, air bubbles, or pit inaccuracies from the manufacturing process, and

So there could be small unwanted particle, dust particles or there could be some air bubbles or things like that which could have happened during manufacturing of these CD's

(Refer Slide Time: 21:16)



The image is a screenshot of a presentation slide. At the top, there is a red header bar with the title "Coding for Compact Disc (CD)" in white text. Below the header, the slide content is on a light gray background. It starts with the section "CD Basics:" followed by a bulleted list of technical details about CD audio encoding. The list includes the disc's diameter, sampling rate, quantization levels, dynamic range, and sources of channel errors like fingerprints and scratches.

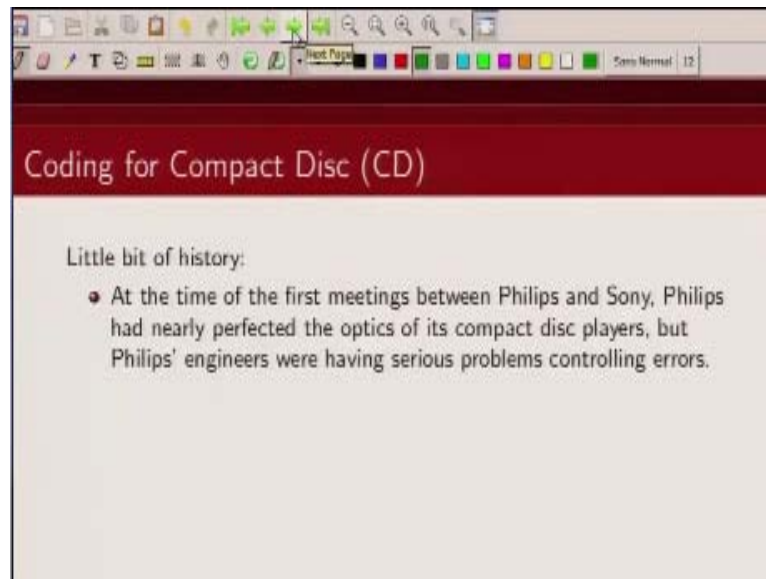
Coding for Compact Disc (CD)

CD Basics:

- The recording medium for CD players is a plastic disc 120 mm in diameter used to store digitized audio in the form of minute pits that are optically scanned by a laser.
- The audio waveform is sampled at 44.1 k samples/s to provide a listening bandwidth of 20 kHz.
- Each audio sample is uniformly quantized to one of 256 levels.
- The resulting dynamic range is 96 dB and the total harmonic distortion is less than 0.005 .
- Sources of channel errors:
 - small unwanted particles, air bubbles, or pit inaccuracies from the manufacturing process, and
 - fingerprints, scratches, or dust particles from handling.

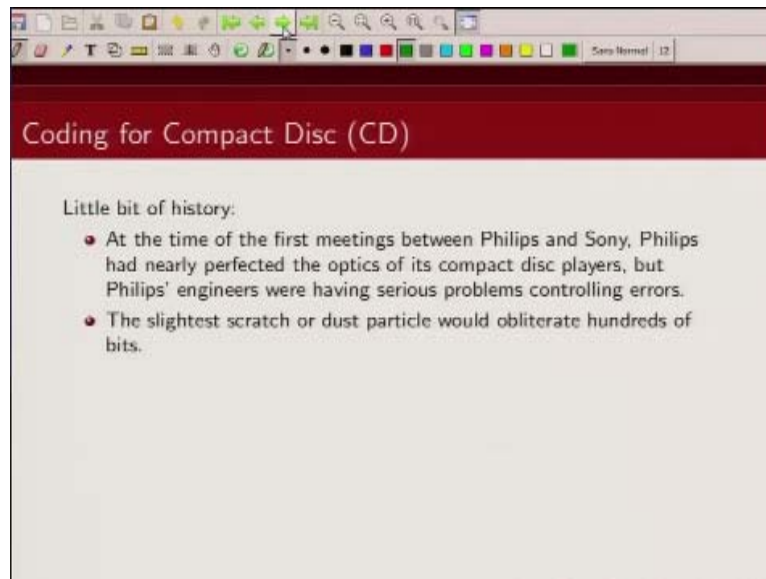
Or fingerprints, scratches, dust particles from handling the CD, so how does a CD corrects or these kinds of errors? You must have noticed even if you have, your CD has small scratches but still your CD plays, so how does it happen?

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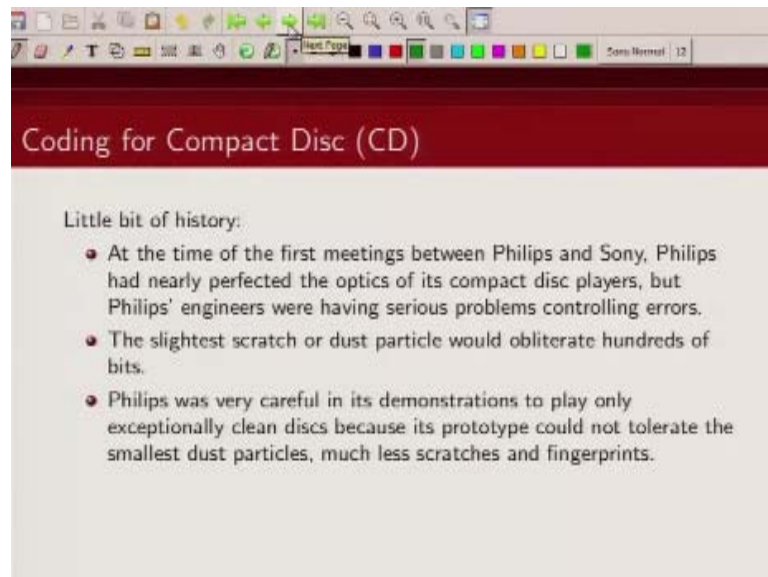
This happens because of a very powerful error control coding which is used in the CD's, so little bit of history basically Philips and Sony were experimenting with this optical disc and Philips engineers had a lot of problems controlling errors.

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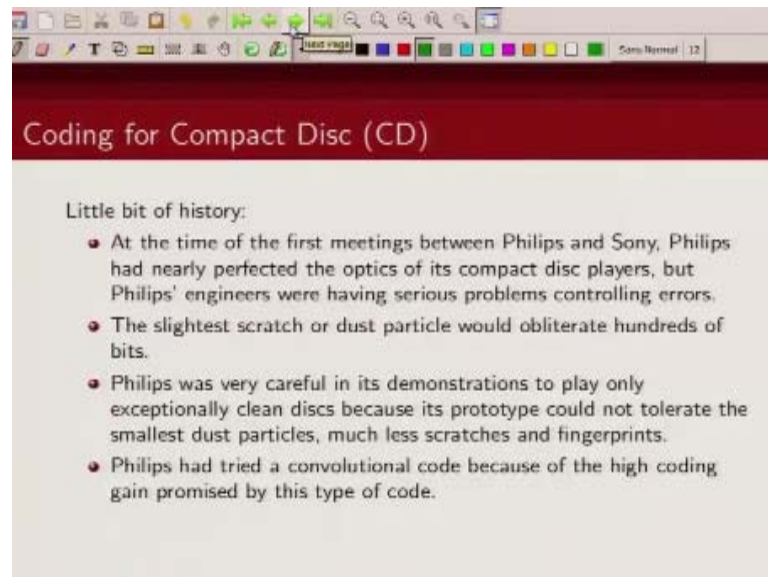
In the disc and even if there would have been small scratches or dust particles the whole data would essentially you know go away

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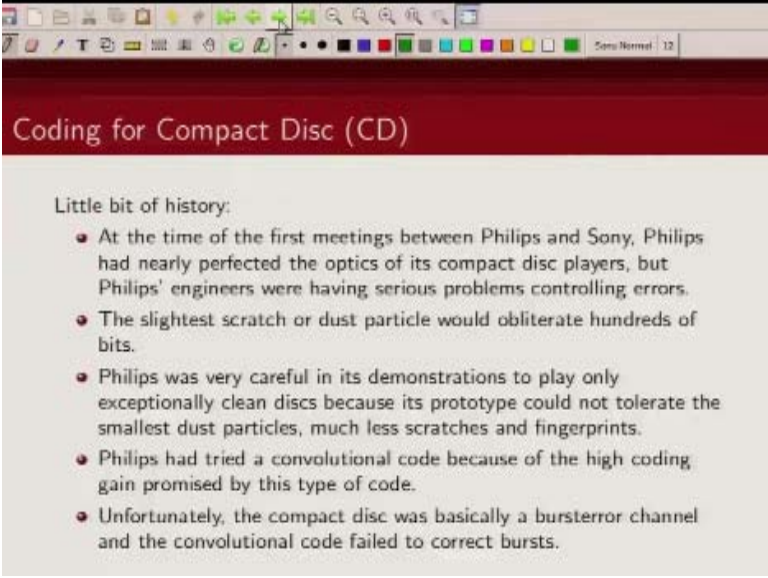
So whenever Philips were demonstrating the CD they were very careful, they were just demonstrating with very, very clean CD's and which did have any scratches and things like that and what Philips.

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Was actually doing was they were trying a convolutional code to correct errors because of high coding gain provided by that but the problem is this storage channel is like an erasure channels, if there is scratch or something like that there are neighboring bits which get affected and the data there is erased, so convolutional codes are not good in correcting erasures and that is why they were initially not successful.

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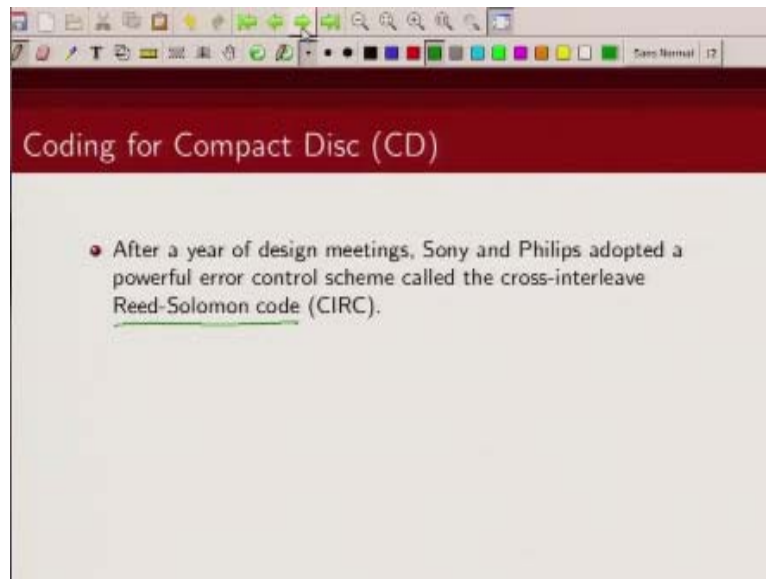
Coding for Compact Disc (CD)

Little bit of history:

- At the time of the first meetings between Philips and Sony, Philips had nearly perfected the optics of its compact disc players, but Philips' engineers were having serious problems controlling errors.
- The slightest scratch or dust particle would obliterate hundreds of bits.
- Philips was very careful in its demonstrations to play only exceptionally clean discs because its prototype could not tolerate the smallest dust particles, much less scratches and fingerprints.
- Philips had tried a convolutional code because of the high coding gain promised by this type of code.
- Unfortunately, the compact disc was basically a bursterror channel and the convolutional code failed to correct bursts.

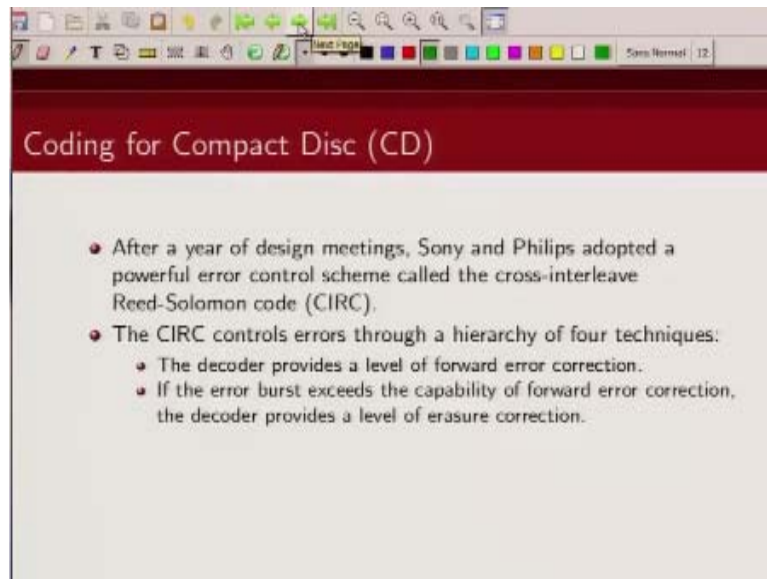
So as I said the problem was this storage media was a burst error correct burst channel, and convolutional codes were not good in correcting burst error, so there comes

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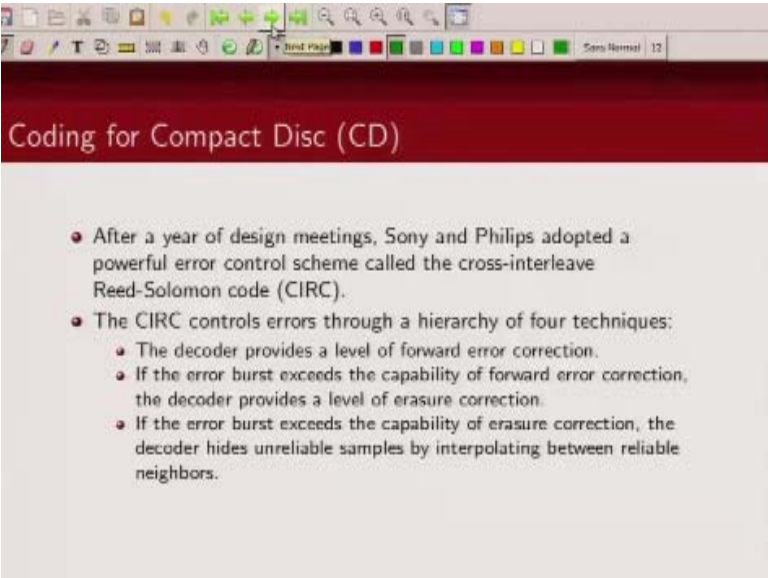
Reed-Solomon code and so the CD's used are basically across interleave Reed-Solomon codes

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And there is you know four set of kind of hierarchy as far as error control and deduction is concerned, so there is an inherent forward error correction because of these Reed-Solomon code, but this the error burst exceeds the capability of the error correcting capability of the code, then the decoder also provides a level of erasure correction so there is a, in addition to error correction there is also an erasure correction and erasure is you know bunch of neighboring bits just getting erased and not just not being able to recover, so the decoder has this capability, if the error corrections fails this, at second level the decoder can do erasure correction and try to recover

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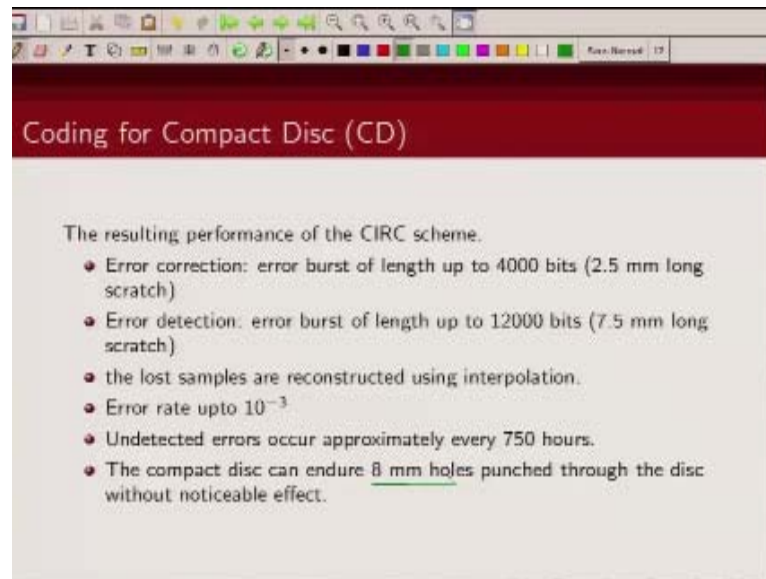
The image is a screenshot of a presentation slide. At the top, there is a dark red header bar with the title "Coding for Compact Disc (CD)" in white text. Below the header, the slide has a light gray background. The content is organized into a bulleted list. The first bullet point states that Sony and Philips adopted a powerful error control scheme called the cross-interleave Reed-Solomon code (CIRC) after a year of design meetings. The second bullet point explains that the CIRC controls errors through a hierarchy of four techniques, which are further detailed in three sub-bullets: forward error correction, erasure correction, and interpolation between reliable neighbors.

Coding for Compact Disc (CD)

- After a year of design meetings, Sony and Philips adopted a powerful error control scheme called the cross-interleave Reed-Solomon code (CIRC).
- The CIRC controls errors through a hierarchy of four techniques:
 - The decoder provides a level of forward error correction.
 - If the error burst exceeds the capability of forward error correction, the decoder provides a level of erasure correction.
 - If the error burst exceeds the capability of erasure correction, the decoder hides unreliable samples by interpolating between reliable neighbors.

Those data, third is if the error burst exceeds the capability of erasure correction then what it does is it tries to do some sort of an interpolation between reliable neighbors so as to interpolate what the data is, and if even interpolation fails then basically the decoder just blanks out and you will hear, like kind of a you know mute sound when the error is big enough that even the interpolation cannot work.

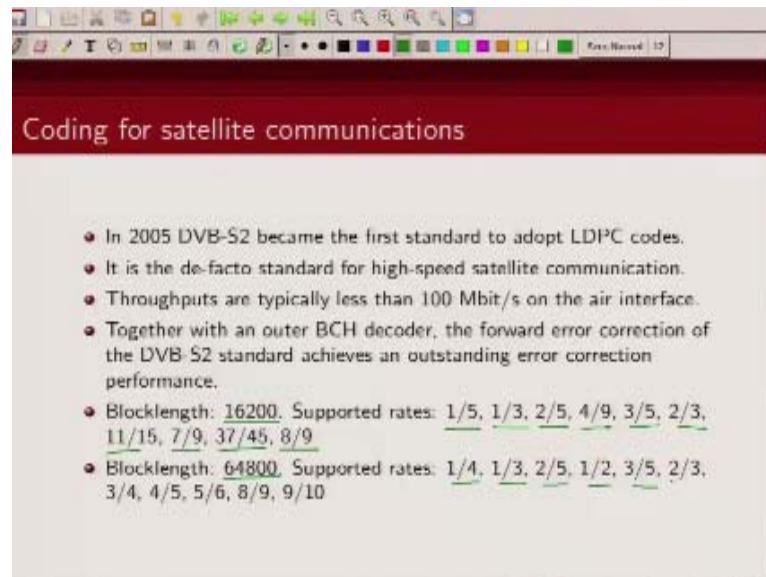
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So a CD disc can correct error burst up to 4000 bits, so try putting a scratch of 2.5mm, your CD will still work, I can guarantee that, it can detect error up to 12000 bits so it can detect errors of up to 27.5mm long scratch, and of course as I said if the error burst exceeds the capability of erasure correction then it tries to do interpolation to get back those steps, and unrated error happens very rarely, it happens every like 750 hours so. So there is a very powerful error correcting codes which are used in, in CD.

And interestingly even these compact disc scan withstands small punch holes in it, you can try putting a 8mm hole into your CD and still it would be able to you know correct the errors in the data and the CD will still work.

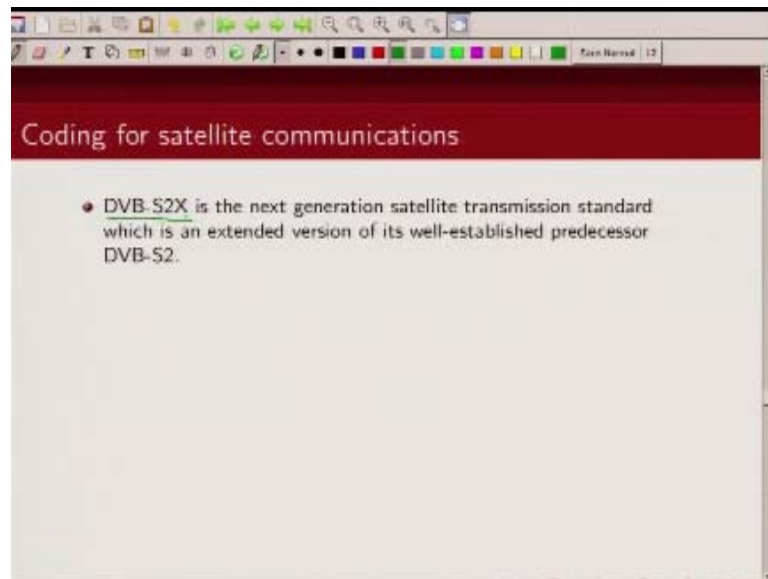
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Now let us move to application for in satellite communication, so there is a standard D, digital video broadcasting is too standard which was one of the first standards to adopt low density parity check codes as their standard, so it is a de-facto standard for high speed satellite communication where typical through put is less than 100 Mbits/s, now it uses as an outer code BCH code along with the inner LDPC codes and it can support variety of block sizes so it arise, it can support a block size of 16,200.

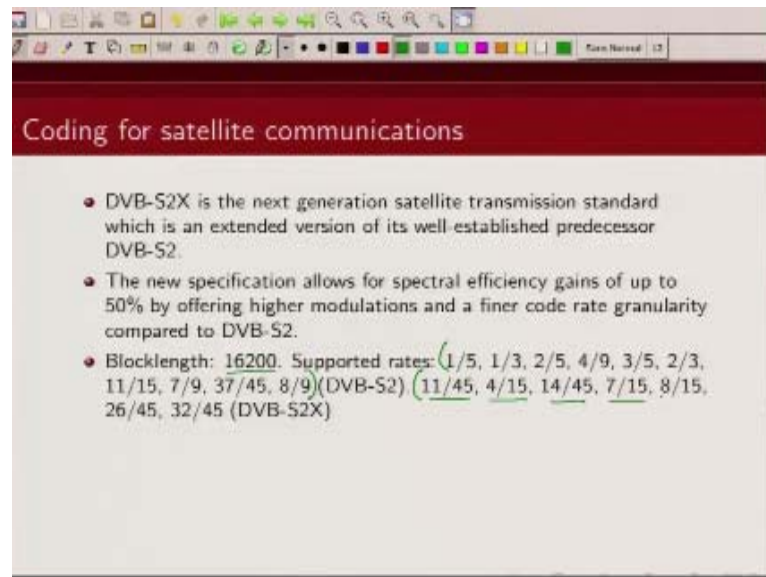
And these are the various code rates that have been supported, so LDPC codes of rate so these are the various rates which have been supported by this standard, similarly for block size of 64,800 these are the various code rates that has been supported in this standard.

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Now there is another standard which is an abridgement of this DVB-S2 standard. Its quality is 2x which is an extended version of DVB-S2 standard.

(Refer Slide Time: 27:00)



Coding for satellite communications

- DVB-S2X is the next generation satellite transmission standard which is an extended version of its well-established predecessor DVB-S2.
- The new specification allows for spectral efficiency gains of up to 50% by offering higher modulations and a finer code rate granularity compared to DVB-S2.
- Blocklength: 16200. Supported rates: $\frac{1}{5}, \frac{1}{3}, \frac{2}{5}, \frac{4}{9}, \frac{3}{5}, \frac{2}{3}, \frac{11}{15}, \frac{7}{9}, \frac{37}{45}, \frac{8}{9}$ (DVB-S2) $\frac{11}{45}, \frac{4}{15}, \frac{14}{45}, \frac{7}{15}, \frac{8}{15}, \frac{26}{45}, \frac{32}{45}$ (DVB-S2X)

And it allows more final rates of LDPC codes, so you can see for the block length of 16,200 these were the rates which were supported by DVB-S2, now the DVB-S2x can support further these rates, so it provides a much finer code rate granularity compared to DVB-S2 standard.

(Refer Slide Time: 27:29)

Coding for satellite communications

- DVB-S2X is the next generation satellite transmission standard which is an extended version of its well-established predecessor DVB-S2.
- The new specification allows for spectral efficiency gains of up to 50% by offering higher modulations and a finer code rate granularity compared to DVB-S2.
- Blocklength: 16200. Supported rates: $1/5$, $1/3$, $2/5$, $4/9$, $3/5$, $2/3$, $11/15$, $7/9$, $37/45$, $8/9$ (DVB-S2), $11/45$, $4/15$, $14/45$, $7/15$, $8/15$, $26/45$, $32/45$ (DVB-S2X)
- Blocklength: 64800. Supported rates: $1/4$, $1/3$, $2/5$, $1/2$, $3/5$, $2/3$, $3/4$, $4/5$, $5/6$, $8/9$, $9/10$ (DVB-S2), $2/9$, $13/45$, $9/20$, $90/180$, $96/180$, $11/20$, $100/180$, $26/45$, $18/30$, $28/45$, $23/36$, $116/180$, $20/30$, $124/180$, $25/36$, $128/180$, $13/18$, $22/30$, $135/180$, $7/9$, $154/180$ (DVB-S2X)

Now similarly for block size of 64,800 you can see these rates that you see here from here starting from here, these rates were not supported in DVB-S2 which are supported in DVB-S2x.

(Refer Slide Time: 27:44)

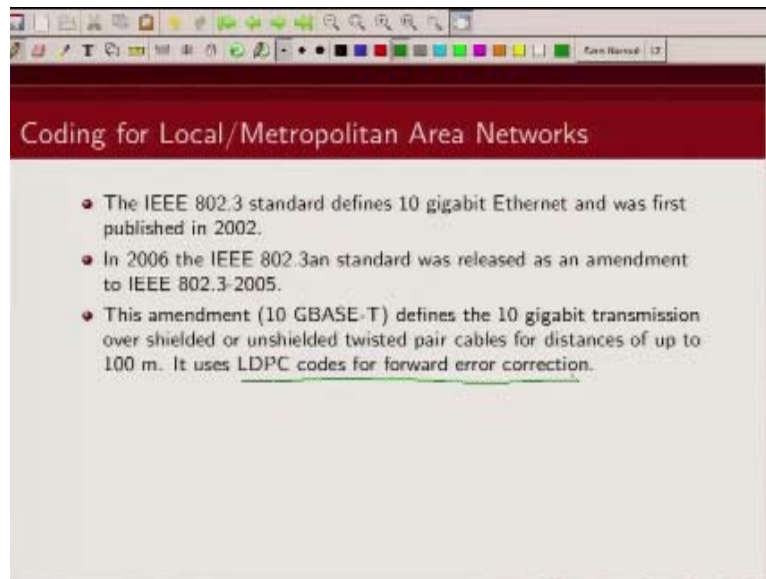
Coding for Deep Space Applications

- The CCSDS (The Consultative Committee for Space Data Systems) published an "experimental specification" for near-earth and deep space communication in 2007.
- In 2011 the LDPC codes were adopted as "recommended standard".

S. No	Blocksize	Information Word	Code Rate
1	8176	7154	7/8
2	1280	1024	4/5
3	1536	1024	2/3
4	2048	1024	1/2
5	5120	4096	4/5
6	6144	4096	2/3
7	8192	4096	1/2
8	20480	16384	4/5
9	24576	16384	2/3
10	32768	16384	1/2

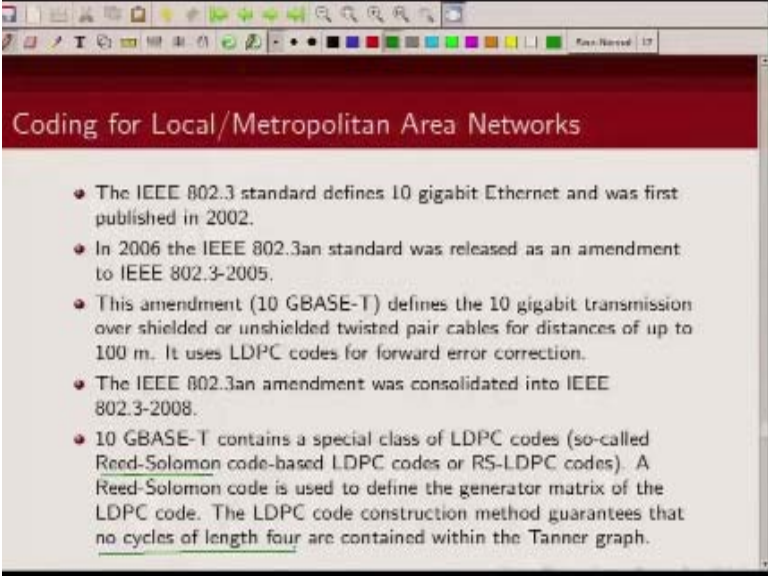
What about these space exploration, now NASA again has specified as recommended standard so these codes that you see here, these are space up, have been prescribed for D space communication and this is for near earth communication so it is for D space communication it up, it supports 3 different block length, information block length 1024, 4096 and 16,384, so these 3 different information block length can be supported and these are the various rates which have been supported, so correspondingly these are the block sizes that you will get.

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Now for 10 gigabits Ethernet also LDPC codes have been suggested, so LDPC codes have been use for forward error correction here, for 10 gigabits Ethernet transmission over Ethernet.

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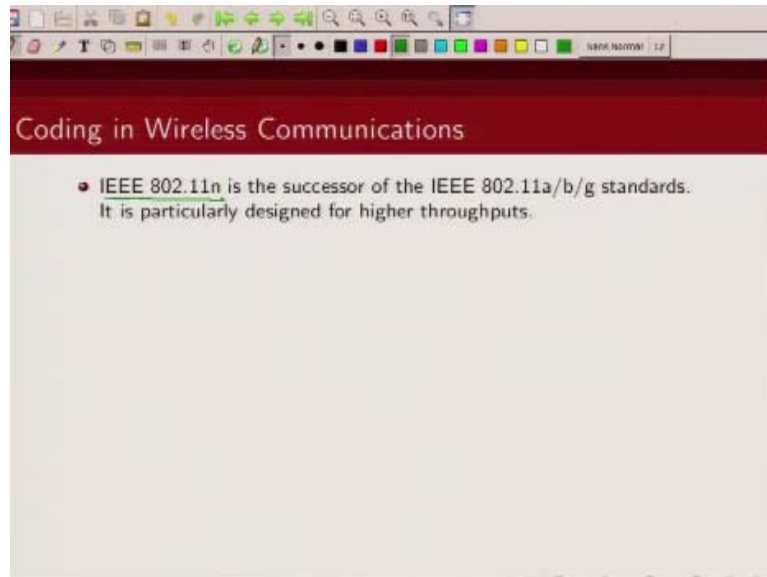


Coding for Local/Metropolitan Area Networks

- The IEEE 802.3 standard defines 10 gigabit Ethernet and was first published in 2002.
- In 2006 the IEEE 802.3an standard was released as an amendment to IEEE 802.3-2005.
- This amendment (10 GBASE-T) defines the 10 gigabit transmission over shielded or unshielded twisted pair cables for distances of up to 100 m. It uses LDPC codes for forward error correction.
- The IEEE 802.3an amendment was consolidated into IEEE 802.3-2008.
- 10 GBASE-T contains a special class of LDPC codes (so-called Reed-Solomon code-based LDPC codes or RS-LDPC codes). A Reed-Solomon code is used to define the generator matrix of the LDPC code. The LDPC code construction method guarantees that no cycles of length four are contained within the Tanner graph.

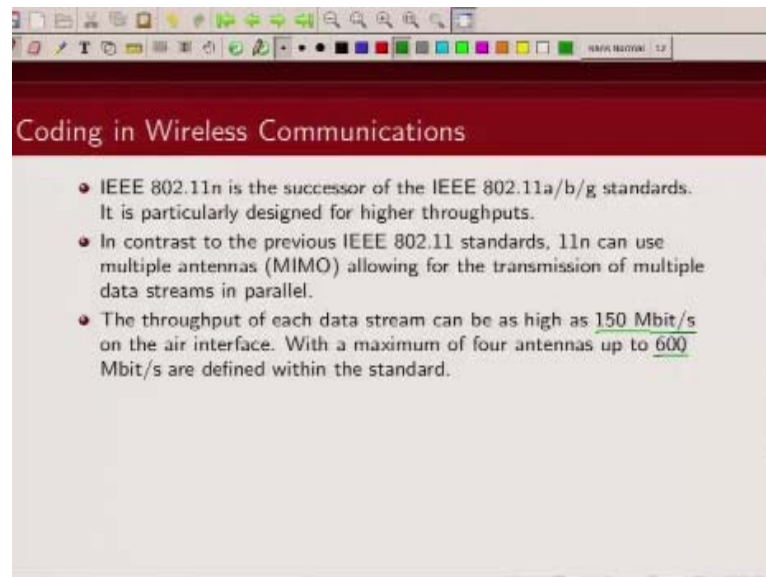
And it uses Reed-Solomon code based LDPC code so the Reed-Solomon code is used to define the generator matrix of LDPC code, and this construction and it shows that there is no cycle, 4 cycles in the LDPC code.

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Now let us move to applications in Wifi, so IEEE 802.11n which is a successor of IEEE 802.11a/b and g. and it supports.

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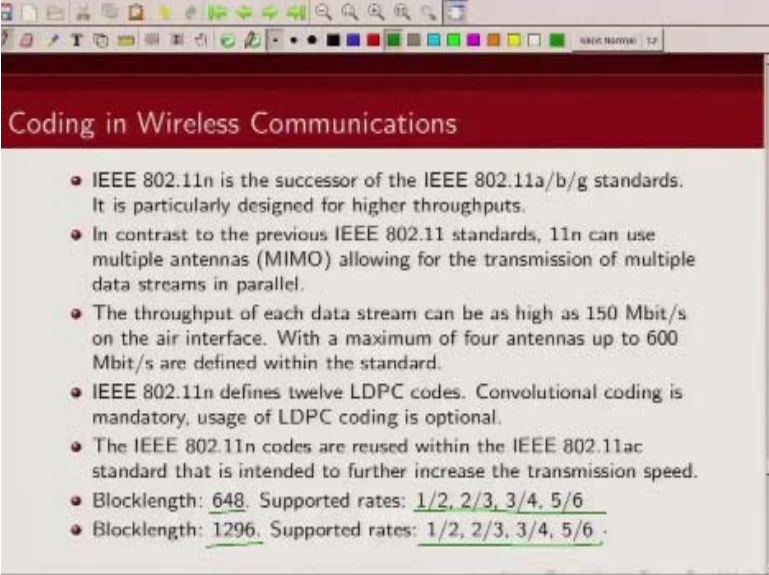


Coding in Wireless Communications

- IEEE 802.11n is the successor of the IEEE 802.11a/b/g standards. It is particularly designed for higher throughputs.
- In contrast to the previous IEEE 802.11 standards, 11n can use multiple antennas (MIMO) allowing for the transmission of multiple data streams in parallel.
- The throughput of each data stream can be as high as 150 Mbit/s on the air interface. With a maximum of four antennas up to 600 Mbit/s are defined within the standard.

Multiple antennas for transmission, so you could get about 150Mbps in each data stream, if you use four antennas can get up to 600 Mbps

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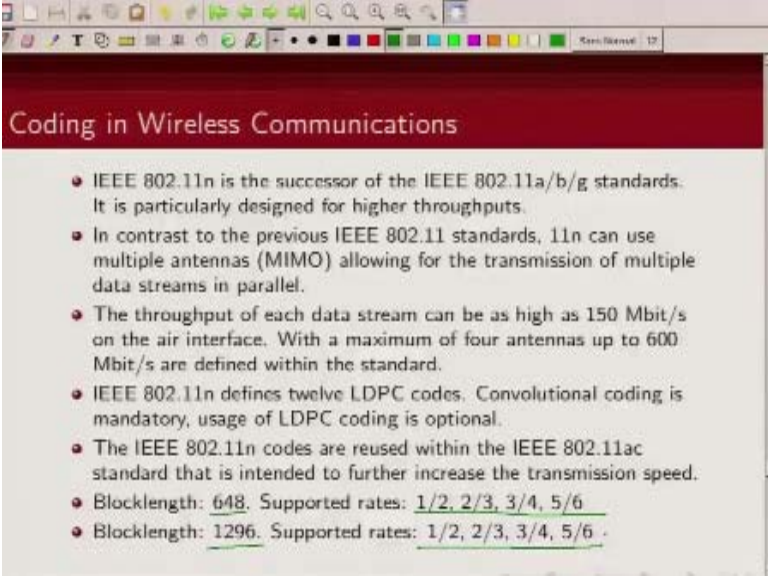


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- IEEE 802.11n defines twelve LDPC codes. Convolutional coding is mandatory, usage of LDPC coding is optional.
- The IEEE 802.11n codes are reused within the IEEE 802.11ac standard that is intended to further increase the transmission speed.
- Blocklength: 648. Supported rates: 1/2, 2/3, 3/4, 5/6
- Blocklength: 1296. Supported rates: 1/2, 2/3, 3/4, 5/6

Now here twelve different LDPC codes have been suggested, now use of LDPC codes in, in this standard is optional, the mandatory requirement is convolutional code. But they have specified LDPC codes which, which are optional which can be used and then these codes have been further reused in this standard 802.11ac to further increase the transmission rate.

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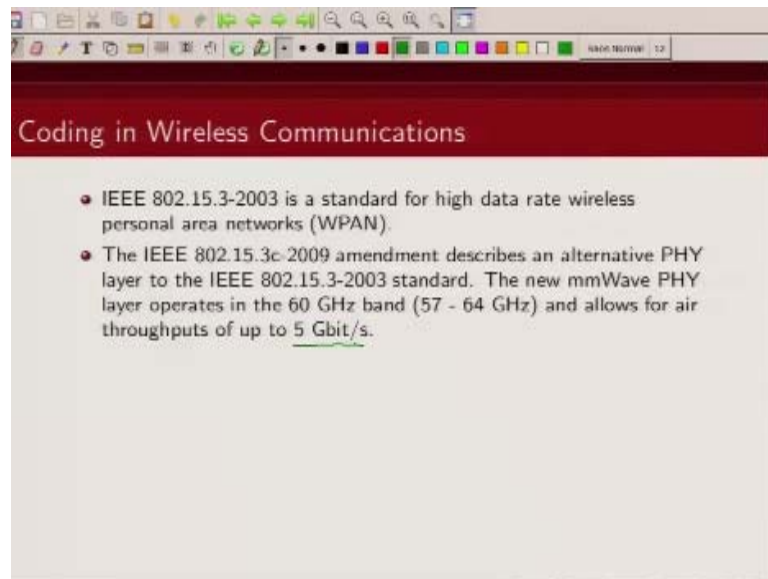


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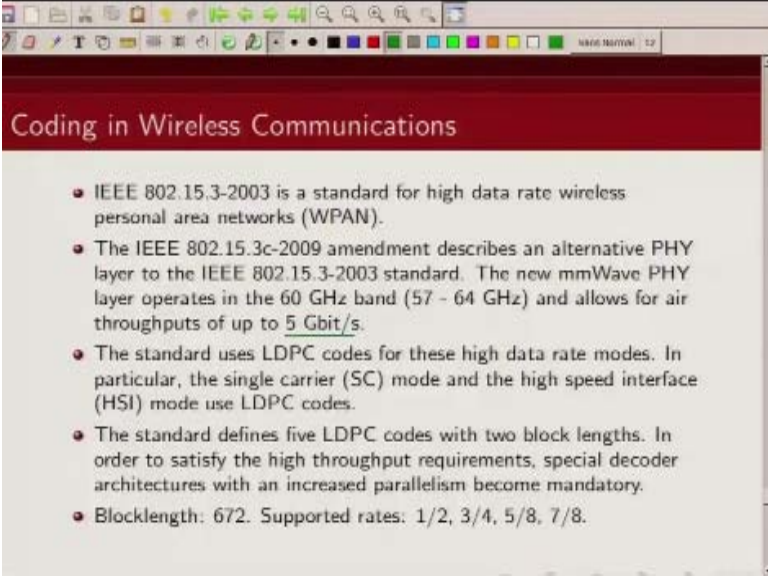
So I list here some of the block lengths which have been supported. So block lengths 648 and these are the various code rates supported here. Similarly, for a block length of 1296 these are the various code rates which have been supported.

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Then we have IEEE 802.15 which is a standard for wireless personal area network. Here also there is a new PHY layer which is based on millimeter wave in 60GHz band which allows throughput up to 5 Gbit/s.

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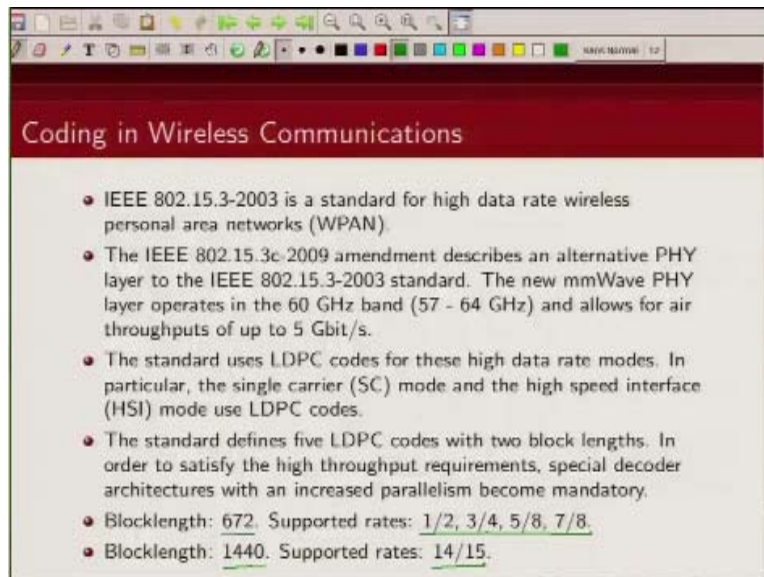


Coding in Wireless Communications

- IEEE 802.15.3-2003 is a standard for high data rate wireless personal area networks (WPAN).
- The IEEE 802.15.3c-2009 amendment describes an alternative PHY layer to the IEEE 802.15.3-2003 standard. The new mmWave PHY layer operates in the 60 GHz band (57 - 64 GHz) and allows for air throughputs of up to 5 Gbit/s.
- The standard uses LDPC codes for these high data rate modes. In particular, the single carrier (SC) mode and the high speed interface (HSI) mode use LDPC codes.
- The standard defines five LDPC codes with two block lengths. In order to satisfy the high throughput requirements, special decoder architectures with an increased parallelism become mandatory.
- Blocklength: 672. Supported rates: 1/2, 3/4, 5/8, 7/8.

Now here LDPC codes have been suggested, now five different LDPC codes for two different block length have been suggested. Now typically the block size here is smaller so as to ensure and also there is architecture research that because we have to get five throughput up to 5 Gbit/s, so architecture research that there is lot of parallelism and the decoder.

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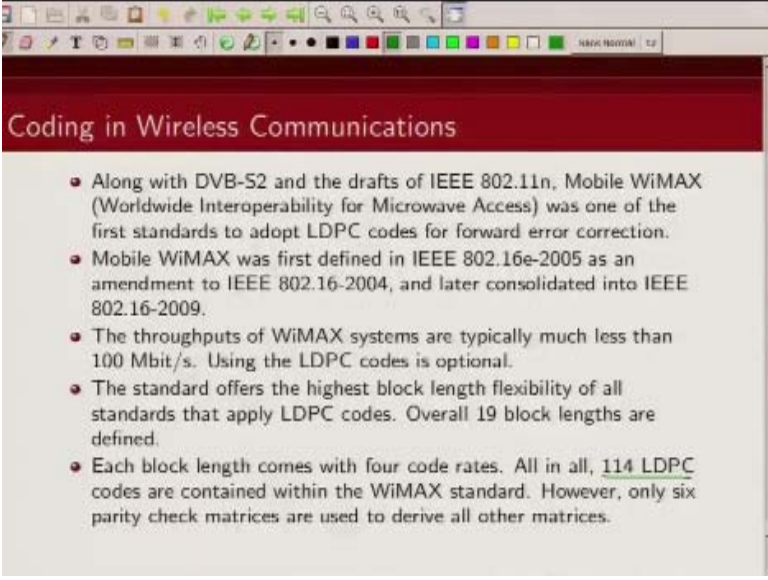


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- Blocklength: 672. Supported rates: 1/2, 3/4, 5/8, 7/8.
- Blocklength: 1440. Supported rates: 14/15.

Can be implemented in parallel, so the rates which have supported, so block size 672 and these are the rate code rates which are supported here. Similarly for block length of 1440 a code rate of 14/15 has been supported.

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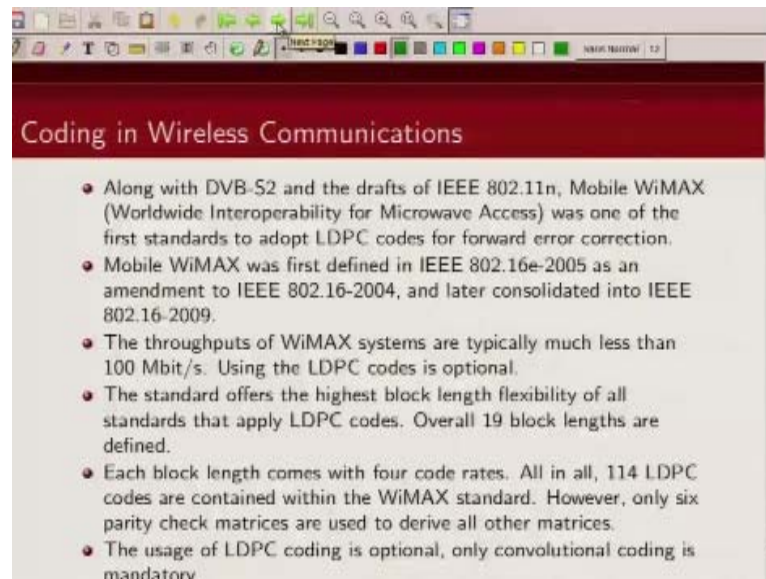


Coding in Wireless Communications

- Along with DVB-S2 and the drafts of IEEE 802.11n, Mobile WiMAX (Worldwide Interoperability for Microwave Access) was one of the first standards to adopt LDPC codes for forward error correction.
- Mobile WiMAX was first defined in IEEE 802.16e-2005 as an amendment to IEEE 802.16-2004, and later consolidated into IEEE 802.16-2009.
- The throughputs of WiMAX systems are typically much less than 100 Mbit/s. Using the LDPC codes is optional.
- The standard offers the highest block length flexibility of all standards that apply LDPC codes. Overall 19 block lengths are defined.
- Each block length comes with four code rates. All in all, 114 LDPC codes are contained within the WiMAX standard. However, only six parity check matrices are used to derive all other matrices.

Now another standard where LDPC codes have been used has been from very beginning is this WiMax and there are lots of codes which have been defined in this WiMax standard, again use of LDPC code is optional here, but they have suggested lot of flexibility as far as block length is concerned and 19 different block lengths have been considered and various different rates have been considered. Total of 114 LDPC codes have been you know defined or contained in this WiMax standard.

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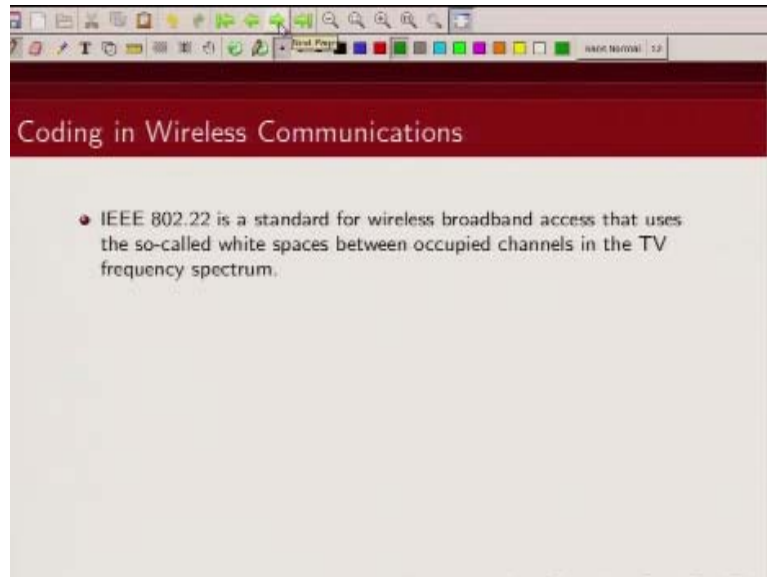


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- Each block length comes with four code rates. All in all, 114 LDPC codes are contained within the WiMAX standard. However, only six parity check matrices are used to derive all other matrices.
- The usage of LDPC coding is optional, only convolutional coding is mandatory.

And as I said, here also the use of LDPC codes is optional; the mandatory requirement is convolutional code.

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And finally I will conclude this discussion with IEEE 802.22 standard which is basically for cognitive radio opportunistic access over TV white spaces.

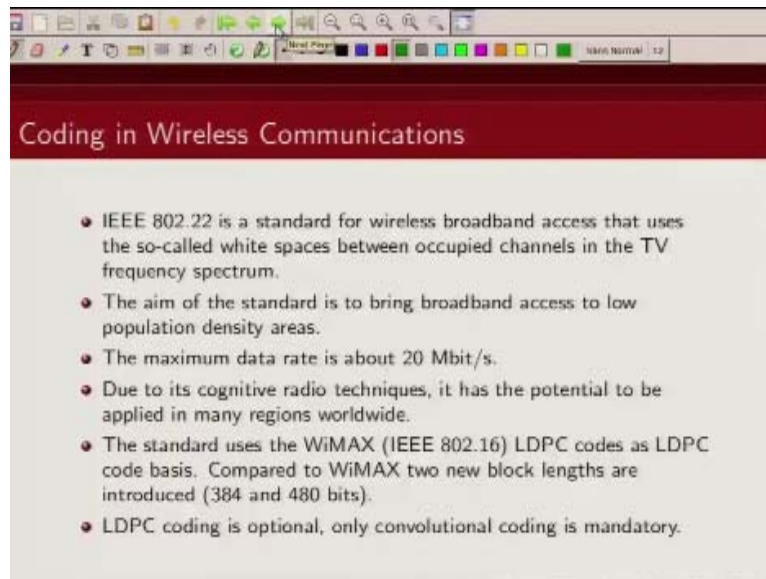
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Coding in Wireless Communications

- IEEE 802.22 is a standard for wireless broadband access that uses the so-called white spaces between occupied channels in the TV frequency spectrum.
- The aim of the standard is to bring broadband access to low population density areas.
- The maximum data rate is about 20 Mbit/s.
- Due to its cognitive radio techniques, it has the potential to be applied in many regions worldwide.
- The standard uses the WiMAX (IEEE 802.16) LDPC codes as LDPC code basis. Compared to WiMAX two new block lengths are introduced (384 and 480 bits).

The TV spectrum which has not been used for coming which is not, which can be opportunistically used for communication and the whole idea of IEEE 802.22 2 is to provide rural connectivity. So here also they have specified lots of various LDPC codes and in fact they have two different, two new block lengths which were not there in WiMax have been added, one corresponding to 384 bits and another corresponding to 480 bits. So this is another application where

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LDPC code is optional; convolutional code is mandatory but LDPC code is optional has been suggested. So this is not an exhaustive list of application, I just wanted to give you some flavor of where in practice we use linear block codes. Thank you.

Acknowledgement

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