

# My journey on Network Coding, Opportunistic Routing, & Related Ideas

Peter Larsson

2016-02-18

NC=network coding, OR=opportunistic routing

# Abstract

- In this talk, I give an overview of some work I did in the past on network coding, opportunistic routing, and some related areas. The focus is on the key-ideas (rather than an in-depth mathematical analysis) and I discuss what influences lead to this work, and how the work unfolded.

# Outline

- Part I:
  - From 2004 and back to paleolithic time
- Part II:
  - From 2004 and onwards to the future

From 2004 and back to paleolithic time

# **PART I**

# WS at UCSD Apr. 2004

**FUTURE GENERATION  
WIRELESS SYSTEMS**

**03.30.2004 - 03.31.2004**

**Ericsson/Cal-(IT)<sup>2</sup> Research  
Review & Workshop  
AGENDA**

**TUESDAY, MARCH 30 (Research Review) Location: CMRR**

8:00 AM - 10:00 AM Adaptive Systems  
10:00 AM - 12:00 PM CDMA Systems  
12:00 PM - 1:00 PM Lunch (CMRR)  
1:00 PM - 2:30 PM Linear Power Amplifiers  
2:30 PM - 4:30 PM Multi-Antenna Wireless Communication Systems  
5:00 PM - 9:00 PM Posters / Demos / Dinner (Location: ERC College - Great Hall)  
- 5:00 PM - 6:30 PM » Posters / Demos and cocktails / hors d'oeuvres  
- 6:30 PM - 7:30 PM » Speakers / Presentations  
- 7:30 PM - 9:00 PM » Buffet dinner

**WEDNESDAY, MARCH 31 (Workshop) Location: CMRR**

8:00 AM - 9:30 AM New "ideas" in wireless communications  
- A. Orlitsky: Recent results in information theory -- Impact on future wireless systems  
- L. Milstein: Ultra-Wideband  
- K. Zeger: Network information flows and coding -- Implications on wireless network capacity

9:30 AM - 12:30 PM Ericsson Contributions  
- Future Network Architectures -- Future public, all IP(v6), wireless network/services architecture (Jan Holler, Eva Gustafsson, Per Johansson)  
- Radio Technologies beyond 3G (beyond CDMA2000 / WCDMA) -- possibilities and challenges (Stefan Parkvall, Shawn Tsai, Young Yoon)  
- Trends in terminal receiver algorithms -- Transceiver improvements that translate into higher system capacity and data rates (Ali Khayrallah)  
- Multi-hop (ad-hoc) wireless networking -- Radio considerations for "smart" ad-hoc routing (Peter Larsson)  
- Cooperation -- Why and How? (Magnus Almgren)

12:30 PM - 1:30 PM LUNCH (CMRR)  
1:30 PM - 2:00 PM New Cal-(IT)<sup>2</sup> Building Tour (construction site)  
2:00 PM - 3:00 PM New Research Initiatives  
- R. Gupta: New Embedded Systems Center -- Next Generation Wireless Devices  
- A. Chien: Center for Network Systems -- New Initiative for Networking Research  
3:00 PM - 5:30 PM Review Feedback from Ericsson and Discussion  
6:30 PM - 8:30 PM Dinner (Location: Faculty Club)

- Attended WS for:
  - Test if I wanted to work in US at UCSD for E///
  - Give a talk on Opportunistic Routing (OR)

- Multi-hop (ad-hoc) wireless networking --  
Radio considerations for "smart" ad-hoc routing  
(Peter Larsson)

# WS at UCSD Apr. 2004

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Implications on wireless network capacity

# WS at UCSD Apr. 2004

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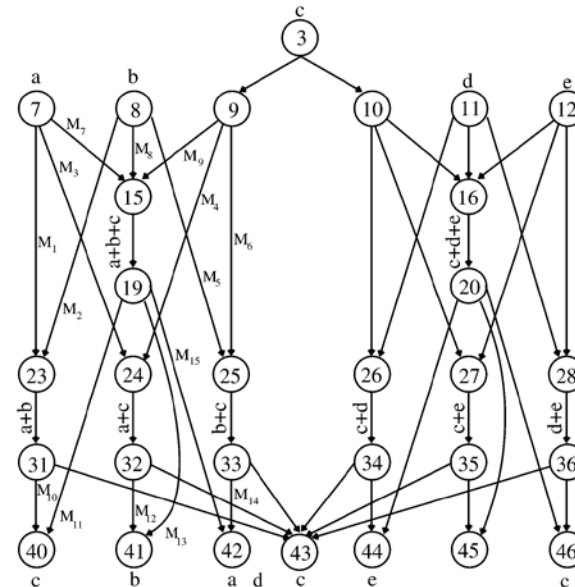
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## • Zeger's Network

### Insufficiency of Linear Coding in Network Information Flow

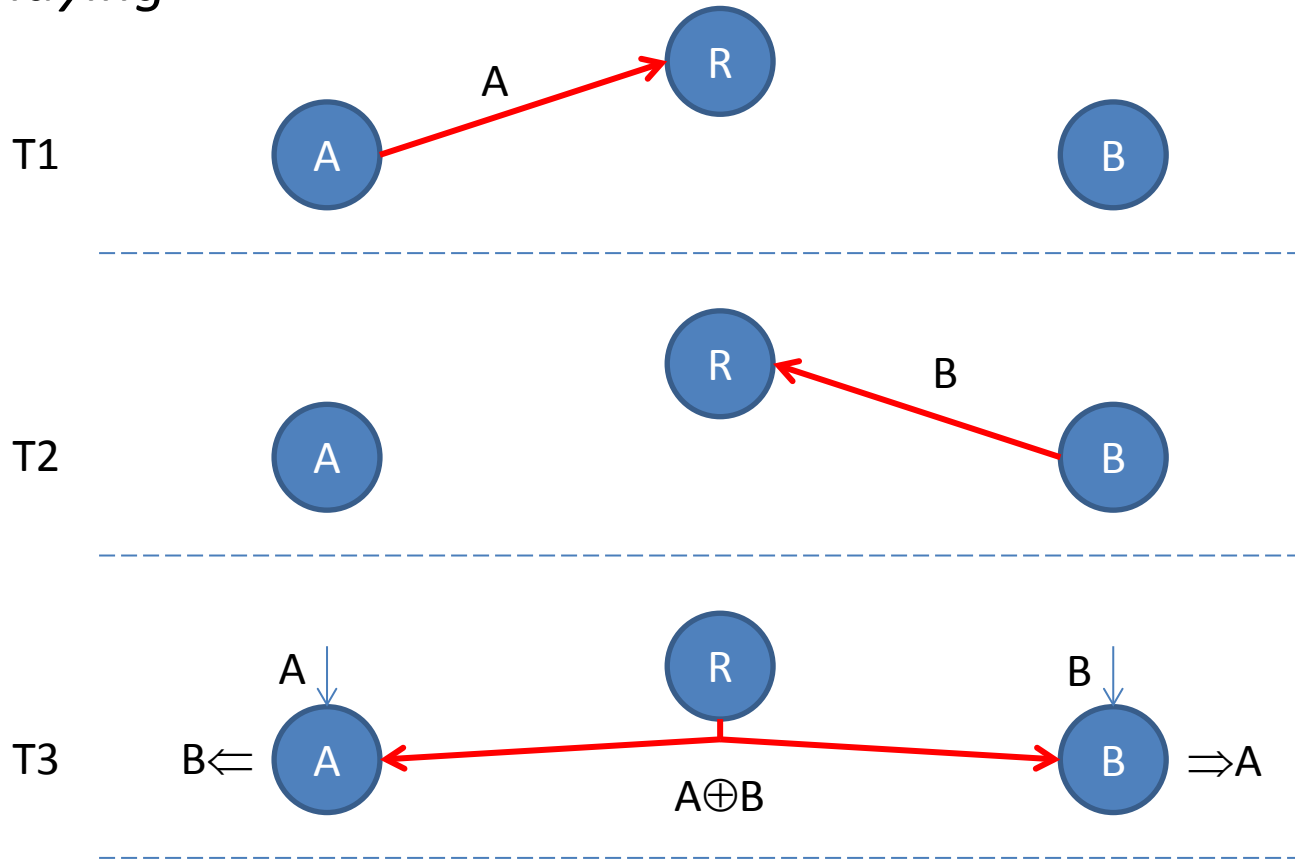
Randall Dougherty, Christopher Freiling, and Kenneth Zeger, *Fellow, IEEE*



- K. Zeger: Network information flows and coding  
Implications on wireless network capacity

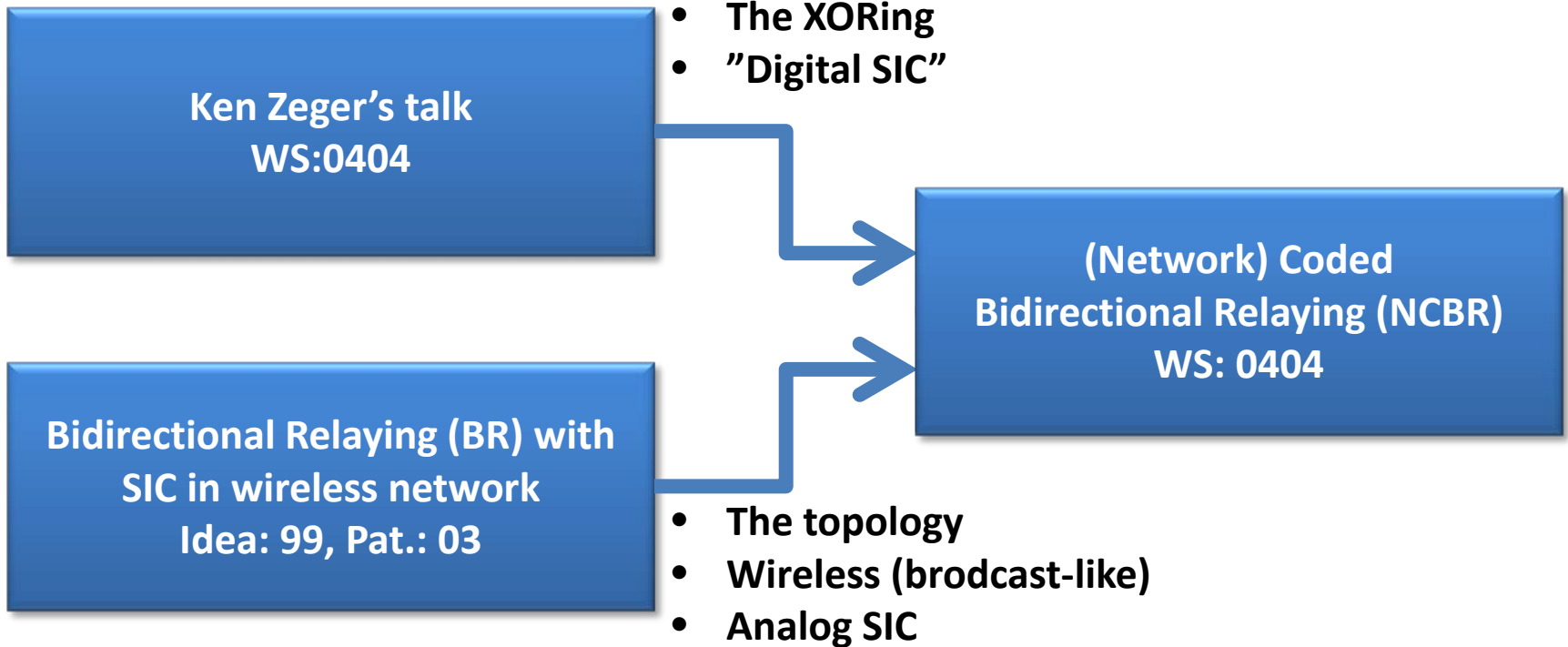
# WS at UCSD Apr. 2004

- And suddenly 😊, I got an idea... *"Coded Bidirectional Relaying"*



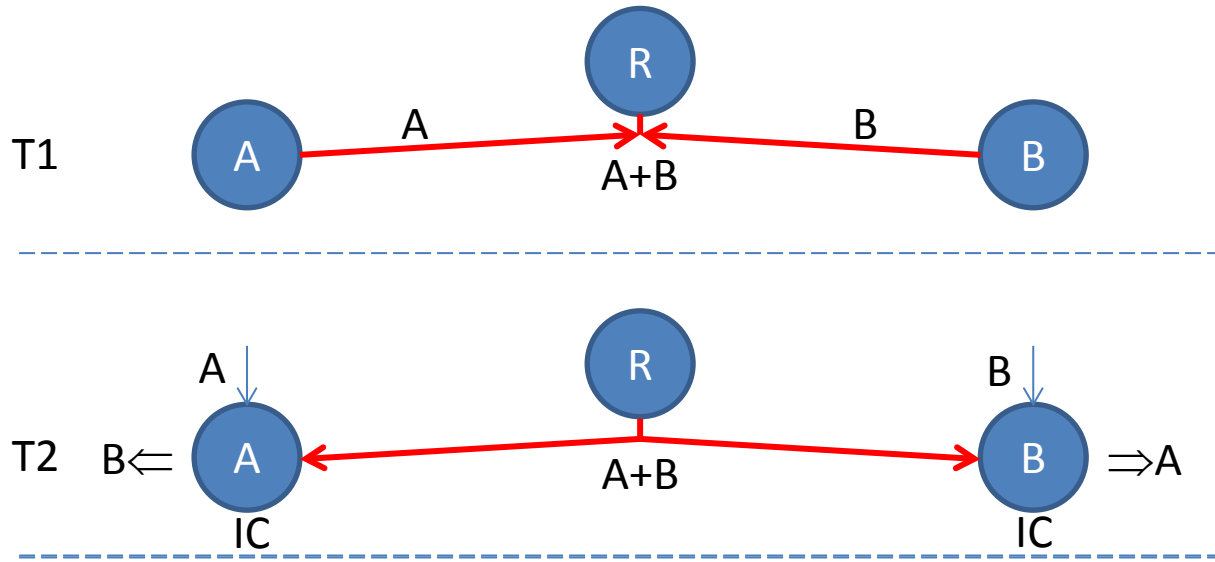


# Why this idea?



# Bidirectional Relaying with SIC

- One calm day in the office (1999-08), with plenty of time that day...



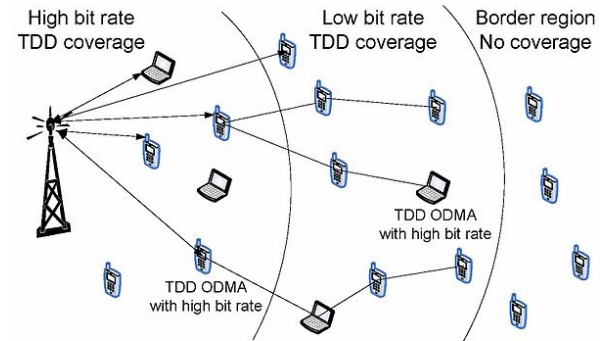
# Why this idea?

Cellular multihop in 3G (ODMA)  
Proj:9908-0008

- **Multihop**

2/4-way Telephone Hybrid  
Hobby: (Age 13-18)

- ....

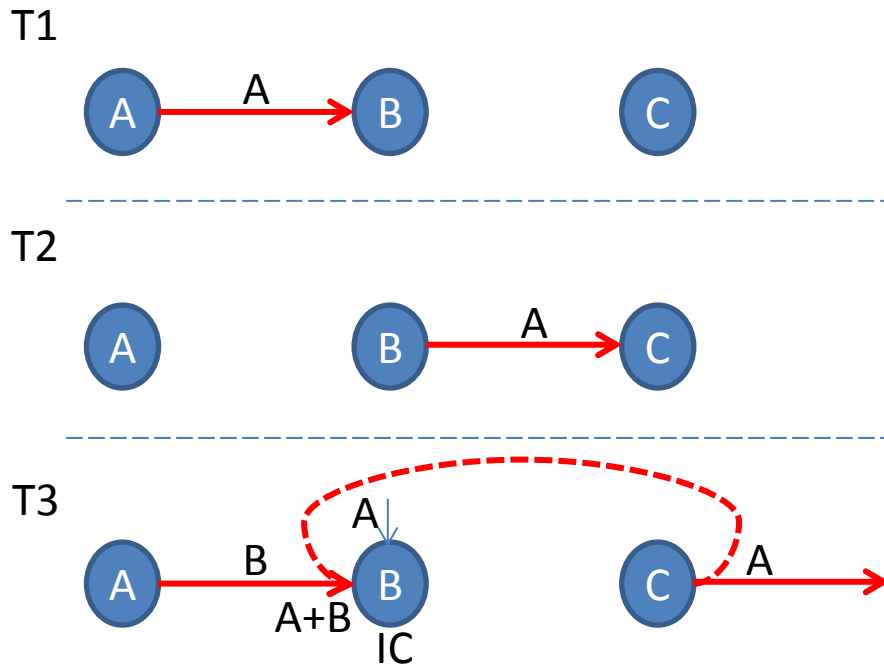


Bidirectional Relaying with SIC  
(Analog network coding)  
Idea: 99, Pat.: 03

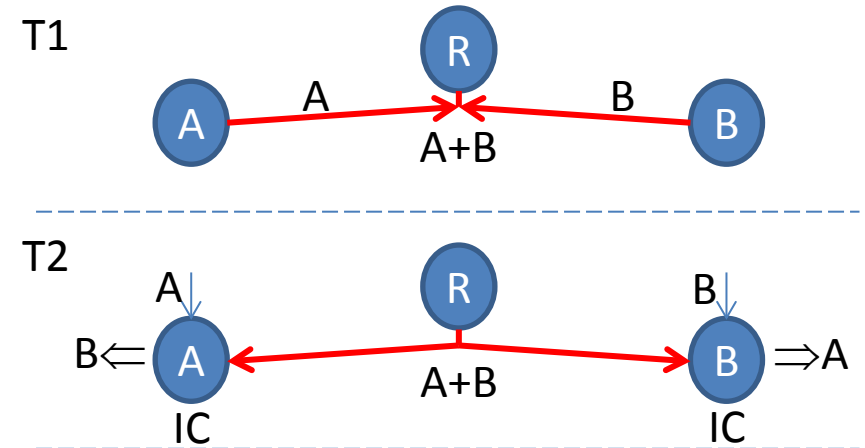
# BR and MH with SIC

- Picked up (and developed) the idea in spring 2000

## Multihop-chain with SIC



## BR with SIC



# How were the two ideas received?

- Closest mngr spring 2000:
  - Message: Not interesting!. "8G!"
- Patent prio board
  - Rejected Oct. 2000
- Years went: 2001, -02, -03
  - Did not see the idea presented elsewhere.  
It had to be good!
  - 2nd try in 2003

# "SIC in Relaying" filed 2003-05



US 20060229017A1

(19) **United States**  
 (12) **Patent Application Publication** (10) **Pub. No.:** US 2006/0229017 A1  
**Larsson et al.** (45) **Pub. Date:** Oct. 12, 2006

(54) **INTERFERENCE CANCELLATION IN WIRELESS RELAYING NETWORKS** (52) **U.S. CL.** ..... 455/63.1; 455/67.13; 455/13.1; 455/24

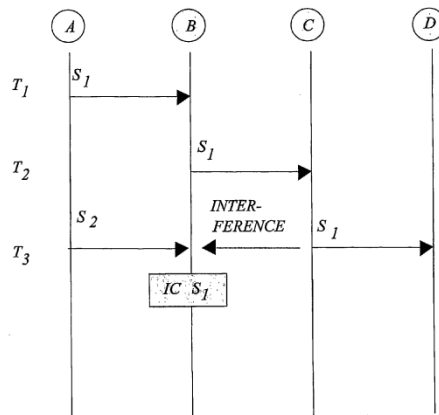
(76) Inventors: **Peter Larsson, Solna (SE); Niklas Johansson, Sollentuna (SE)** (57) **ABSTRACT**

Correspondence Address:  
**NIXON & VANDERHIVE, PC**  
**901 NORTH GLEBE ROAD, 11TH FLOOR**  
**ARLINGTON, VA 22203 (US)**

(21) Appl. No.: **10/549,908**  
 (22) PCT Filed: **Apr. 26, 2004**  
 (86) PCT No.: **PCT/SE04/00633**  
**Related U.S. Application Data**  
 (60) Provisional application No. 60/470,425, filed on May 15, 2003.

**Publication Classification**  
 (51) **Int. Cl.** **H04B 1/00** (2006.01)

In accordance with the invention, signal information representative of a first set of information to be transmitted more than one time over at least one link is stored as a priori known signal information. This could be previously received and/or, detected information, own transmitted information or otherwise available relevant signal information in the node. Signal information representative of a second set of information is received, wherein a transmission of the first set of information interferes with the reception of the second set of information. In spite of the interference, at least part of the second set of information can still be successfully be detected by exploiting the received signal information and at least part of the previously stored a priori known signal information. The information is detected by interference cancellation based on the received signal information and relevant parts of the a priori known information. The set of priori known signal information is preferably updated by continuously storing newly detected information.



US007336930B2

(12) **United States Patent** (10) **Patent No.:** US 7,336,930 B2  
**Larsson et al.** (45) **Date of Patent:** Feb. 26, 2008

(54) **INTERFERENCE CANCELLATION IN WIRELESS RELAYING NETWORKS** (56) **References Cited**

(75) Inventors: **Peter Larsson, Solna (SE); Niklas Johansson, Sollentuna (SE)**  
 (73) Assignee: **Telefonaktiebolaget LM Ericsson (publ), Stockholm (SE)**

(\* ) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **10/549,908**  
 (22) PCT Filed: **Apr. 26, 2004**  
 (86) PCT No.: **PCT/SE2004/000633**  
 § 371 (c)(1).  
 (2), (4) Date: **Sep. 20, 2005**  
 (87) PCT Pub. No.: **WO2004/102891**  
 PCT Pub. Date: **Nov. 25, 2004**

**Prior Publication Data**  
 US 2006/0229017 A1 Oct. 12, 2006

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**H04B 15/00** (2006.01)  
 (52) **U.S. CL.** ..... 455/63.1; 455/13.1; 455/24; 455/67.13; 455/13.1, 455/24, 68.1, 67.1, 67.13  
 (58) **Field of Classification Search** ..... 455/13.1, 455/24, 68.1, 67.1, 67.13  
 See application file for complete search history.

35 Claims, 17 Drawing Sheets

**HIDDEN TERMINAL TO NODE A**



(11) **EP 1 625 697 B1**

(12) **EUROPEAN PATENT SPECIFICATION**

(45) Date of publication and mention of the grant of the patent: **03.10.2012 Bulletin 2012/40** (81) Int. Cl.: **H04L 12/26 (2006.01)** **H04L 27/26 (2006.01)**  
**H04B 1/715 (2011.01)** **H04B 1/7107 (2011.01)**

(21) Application number: **04729571.2** (86) International application number: **PCT/SE2004/000633**  
 (22) Date of filing: **26.04.2004** (87) International publication number: **WO 2004/102891 (25.11.2004 Gazette 2004/48)**

(54) **INTERFERENCE CANCELLATION IN WIRELESS RELAYING NETWORKS**  
**LÖSCHUNG VON STÖRUNGEN IN DRAHTLOSEN RELAISNETZWERKEN**  
**ANNULATION D'INTERFERENCE DANS UN RESEAU RELAIS SANS FIL**

(84) Designated Contracting States: **AT BE BG CH CY CZ DE DK EE ES FI FR GB GR HU IE IT LI LU MC NL PL PT RO SE SI SK TR**  
 • **JOHANSSON, Niklas**  
**S-191 34 Sollentuna (SE)**

(30) Priority: **15.05.2003 US 470425 P**  
 (43) Date of publication of application: **15.02.2006 Bulletin 2006/07**  
 (73) Proprietor: **Telefonaktiebolaget LM Ericsson (publ)**  
**164 83 Stockholm (SE)**

(74) Representative: **Kühn, Friedrich Heinrich Ericsson AB**  
**Patent Unit Kista RAN 2**  
**164 80 Stockholm (SE)**

(56) References cited:  
**US-A- 4 470 138 US-A- 5 596 439**  
 • **TOUMPISS S. ET AL.:** 'Capacity Regions for Wireless Ad Hoc Networks' IEEE INT. CONF. ON COMMUNICATIONS, NY, US vol. 5, April 2002 - May 2002, pages 3168 - 3173, XP001195101

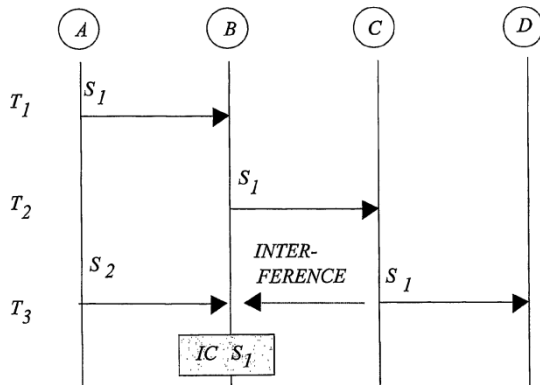
(72) Inventors:  
 • **LARSSON, Peter**  
**S-169 71 Solna (SE)**

EP 1 625 697 B1

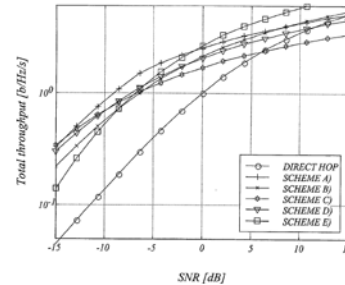
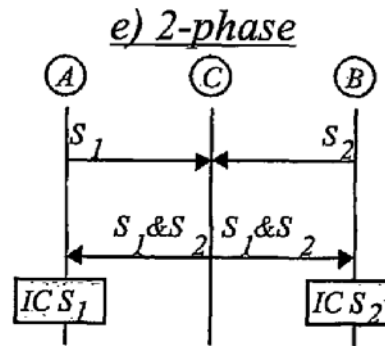
Note: Within nine months of the publication of the mention of the grant of the European patent in the European Patent Bulletin, any person may give notice to the European Patent Office of opposition to that patent. In accordance with the Implementing Regulations. Notice of opposition shall not be deemed to have been filed until the opposition fee has been paid. (Art. 99(1) European Patent Convention).

# Some concepts in "SIC in Relaying"

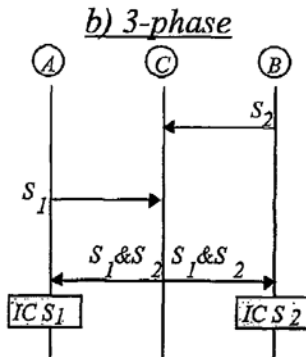
- MH



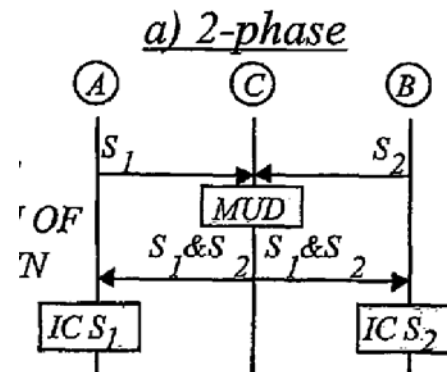
- 2-phase



- 3-phase



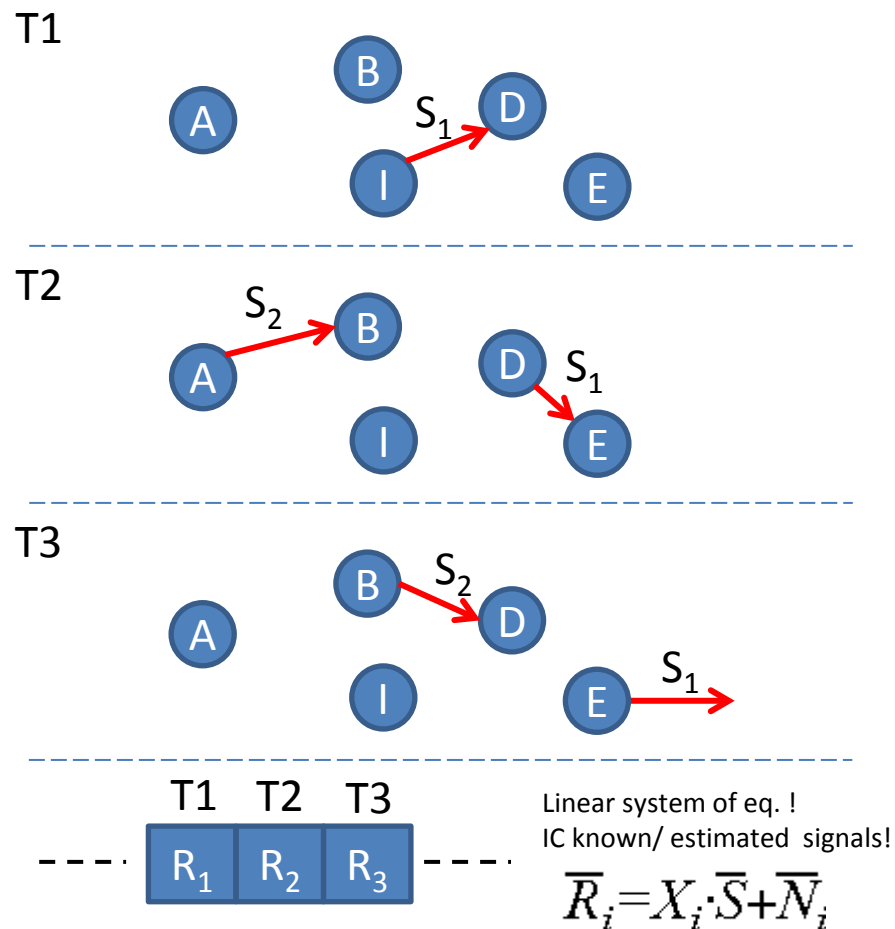
- 2-phase with MUD



N.B. Don't ask me about the "&"

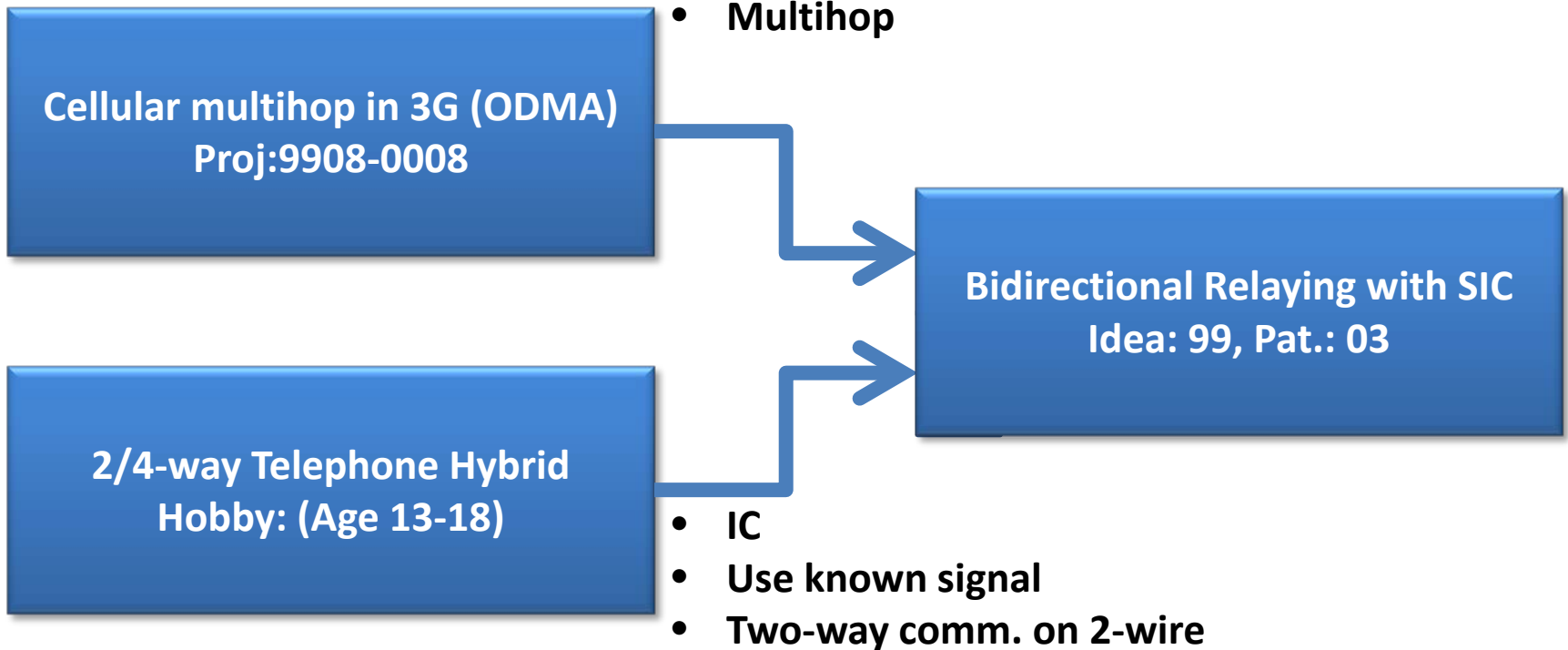
# Some concepts in "SIC in Relaying"

- Self-IC in MH networks

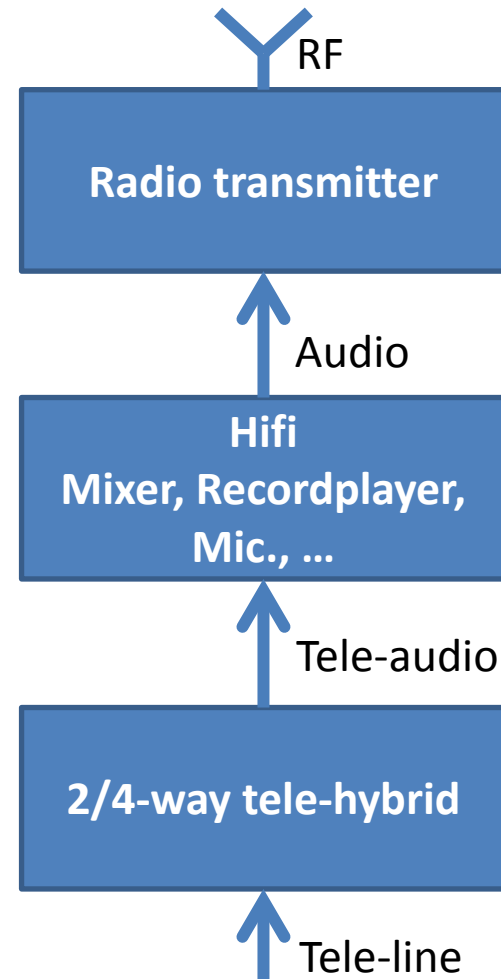
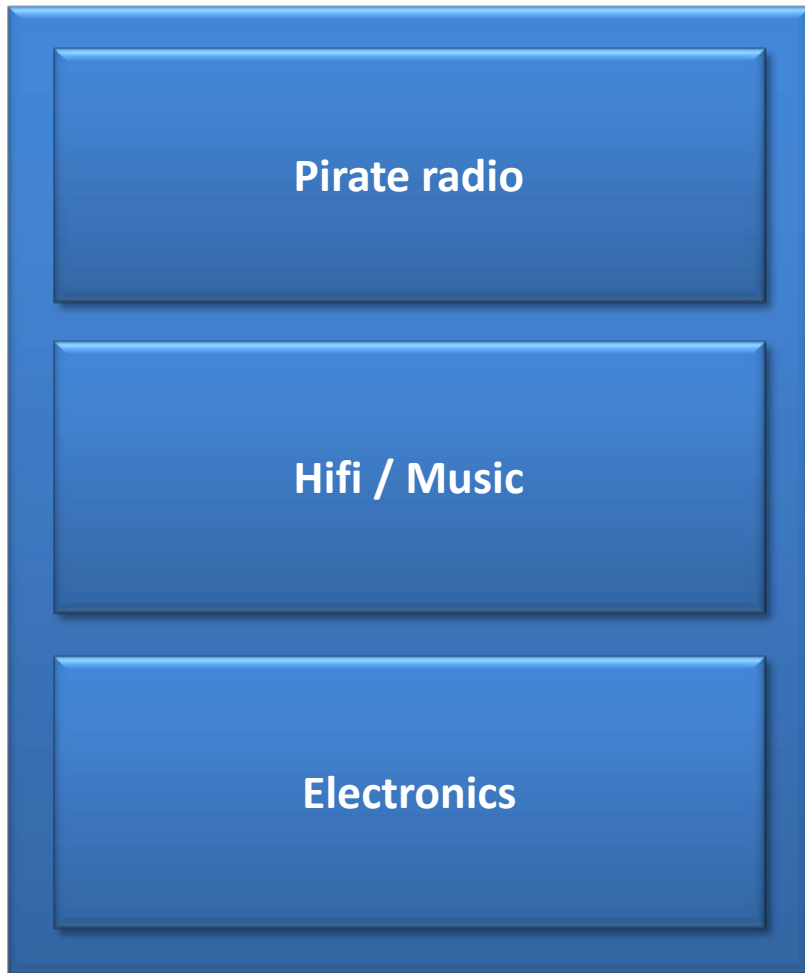




# Why this idea?

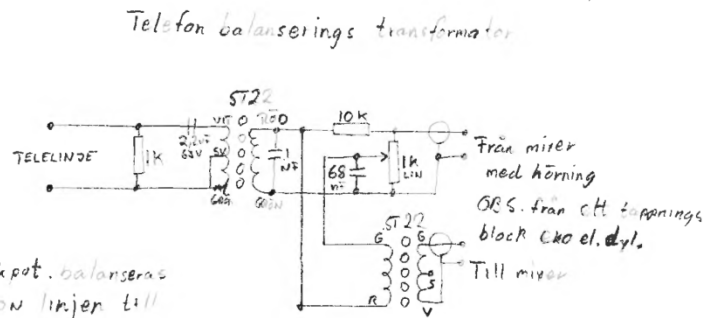


# Why a 2/4-way Telephone Hybrid?



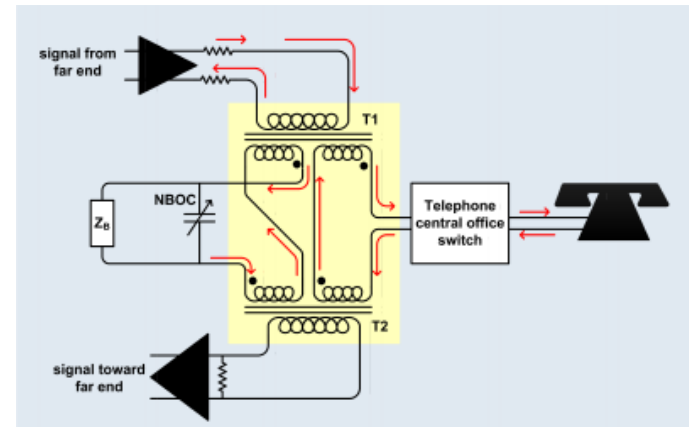
# 2/4-way Telephone hybrid

- A 2/4 tele-hybrid



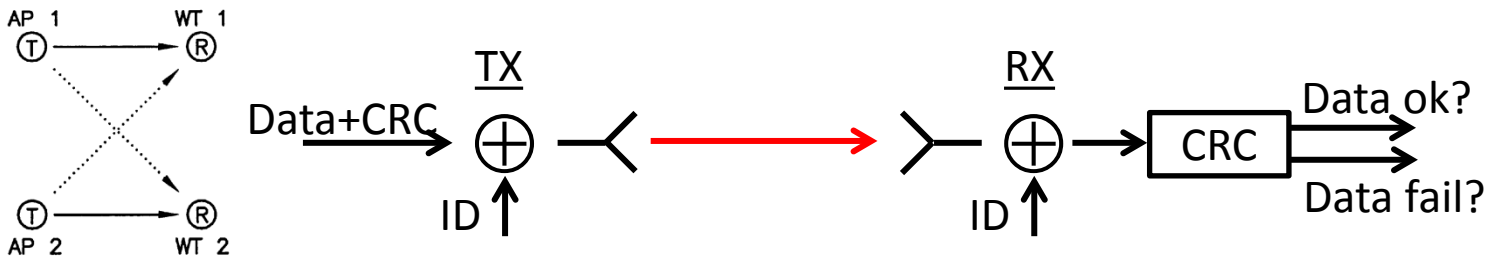
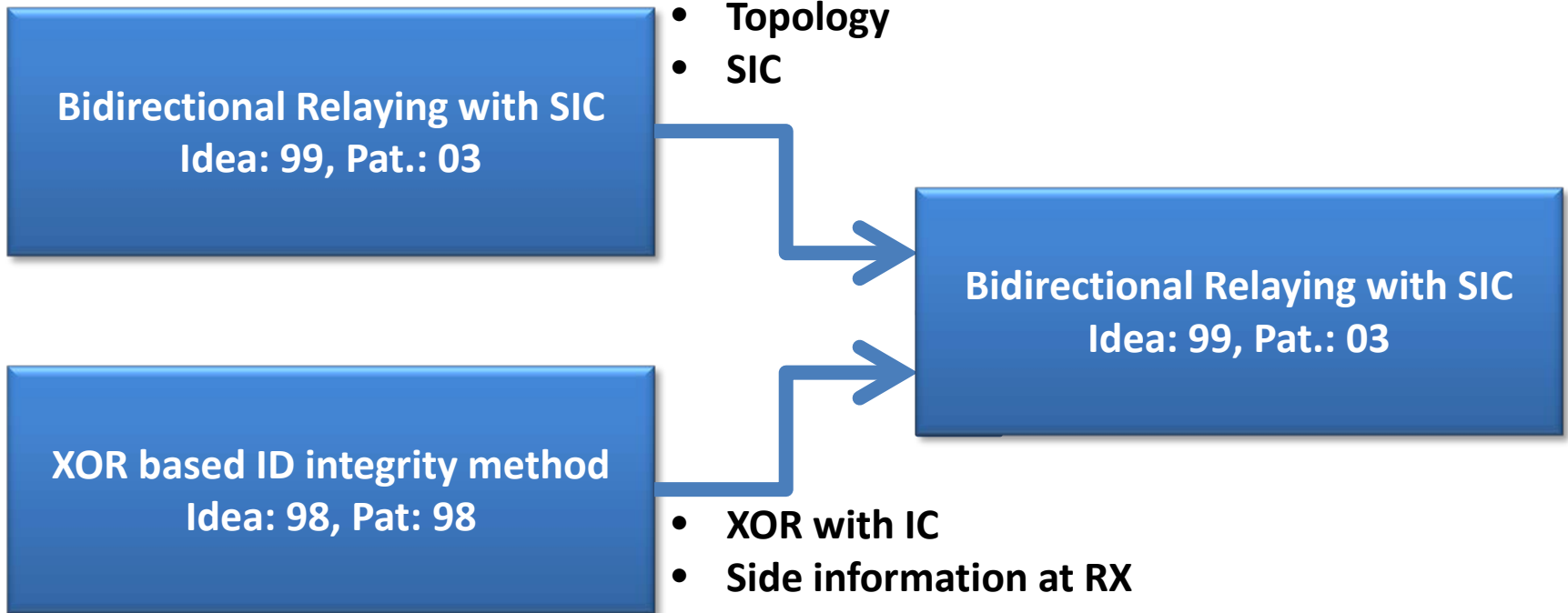
Med 1k pot. balansera telefon linjen till minsta reflexion av den utgåendesignalen från mixern.

- Operation



- What was learned
  - Cancellation possible (IC).
  - Use of a known signal for IC.
  - Bidirectional communication on a 2-wire possible.

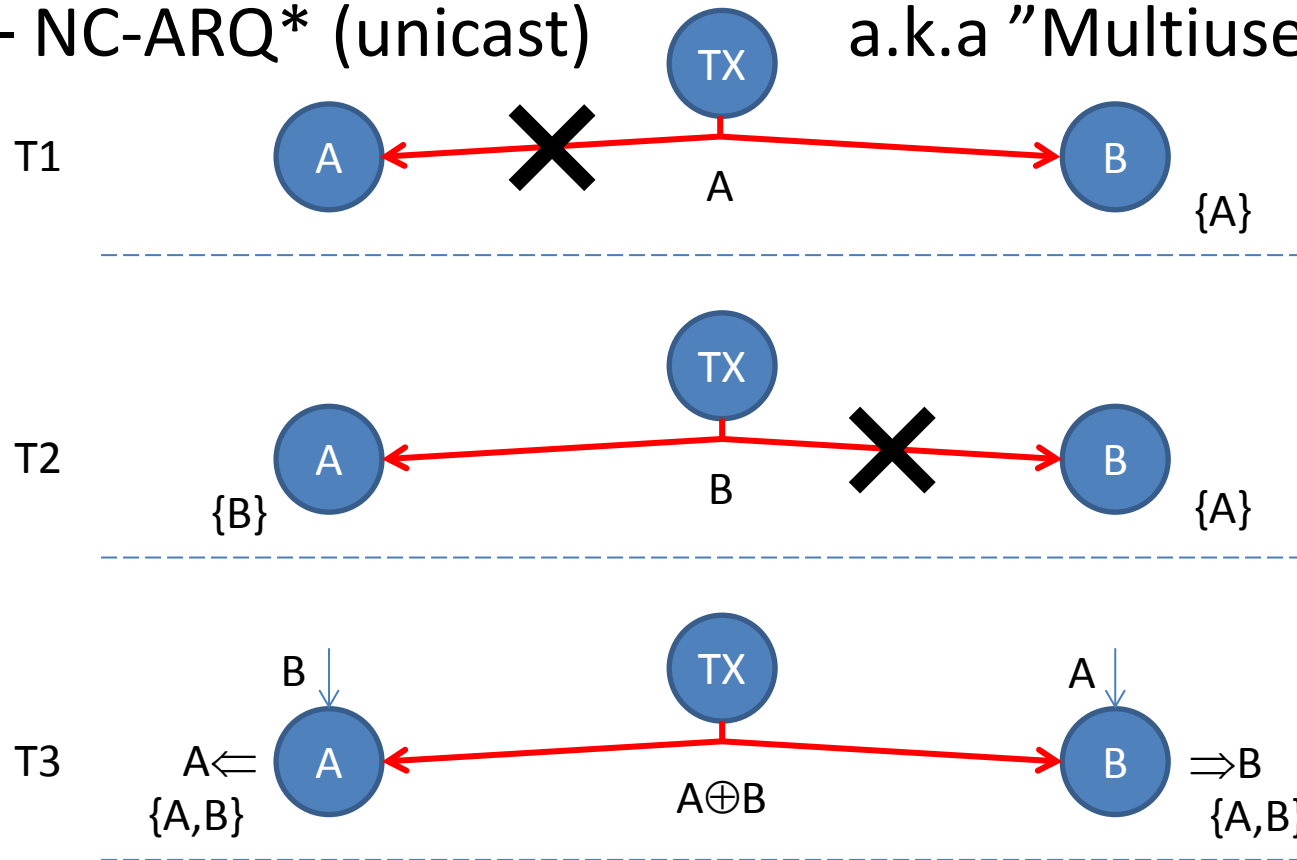
# Why did I not see NCBR earlier?



# Summer 2004, after the UCSD WS

- (N)CBR was a fun idea. Can one do more?

– NC-ARQ\* (unicast) a.k.a "Multiuser-ARQ"

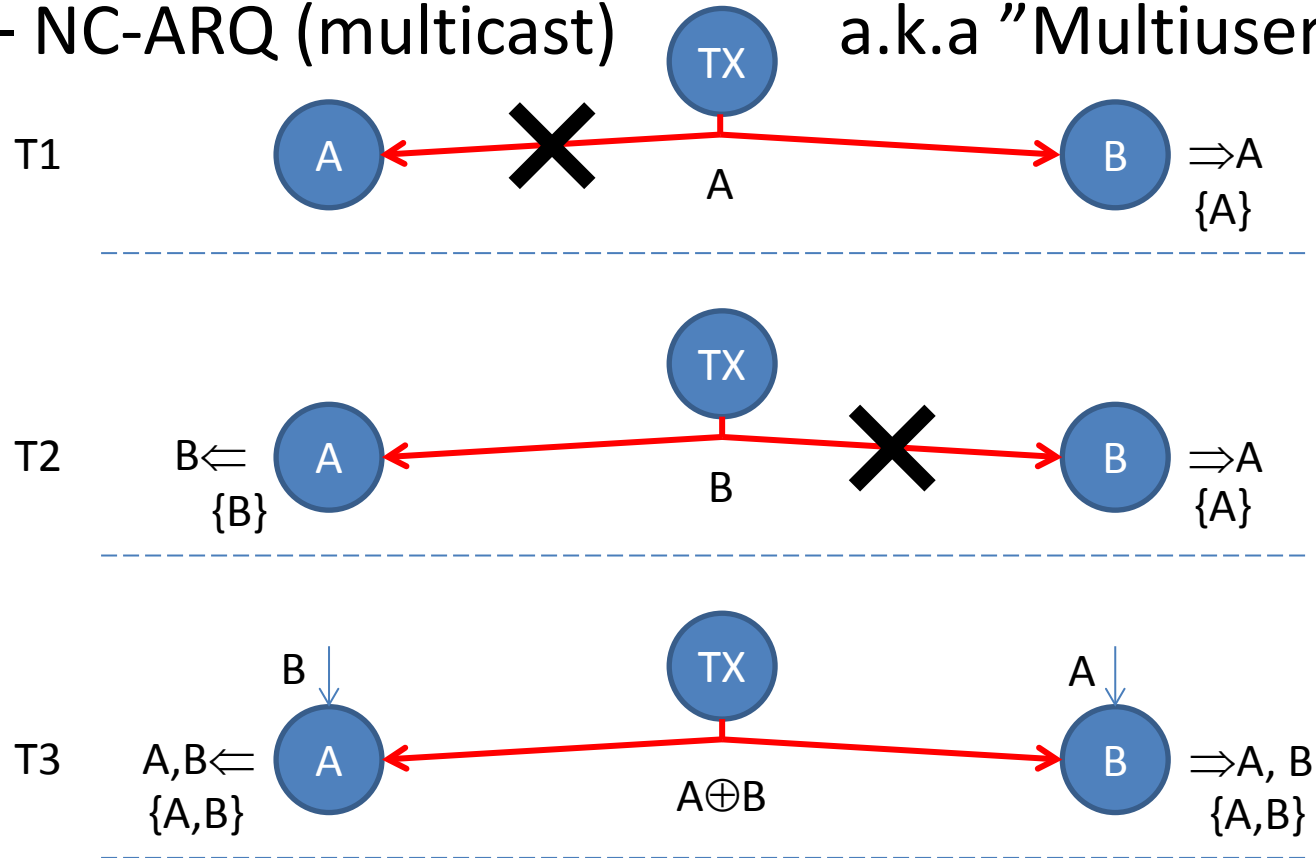


\* Also NC-HARQ (CC and IR) presented (200409)

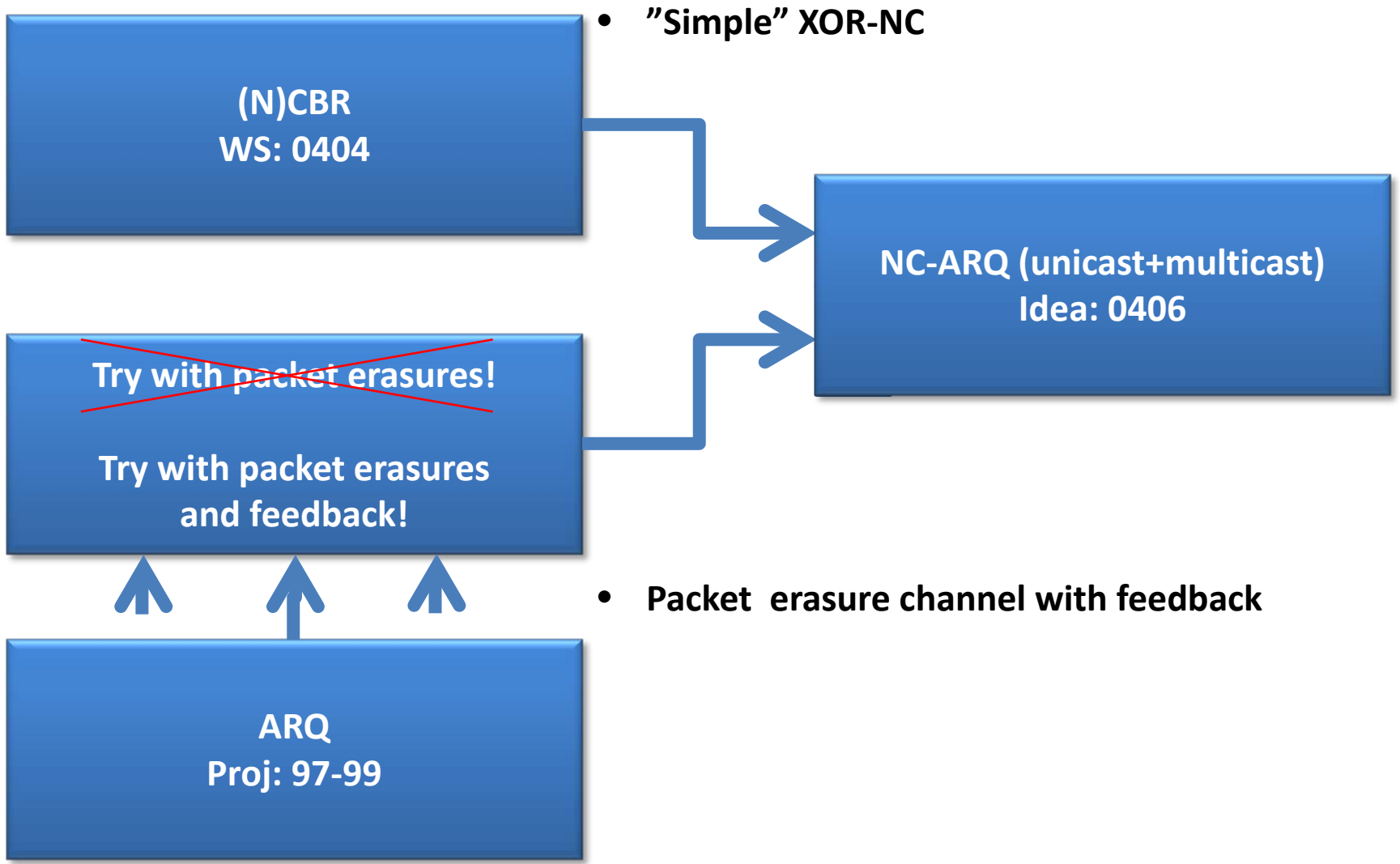
# Summer 2004, after the UCSD WS

- (N)CBR was a fun idea. Can one do more?

– NC-ARQ (multicast) a.k.a "Multiuser-ARQ"



# Why those ideas?



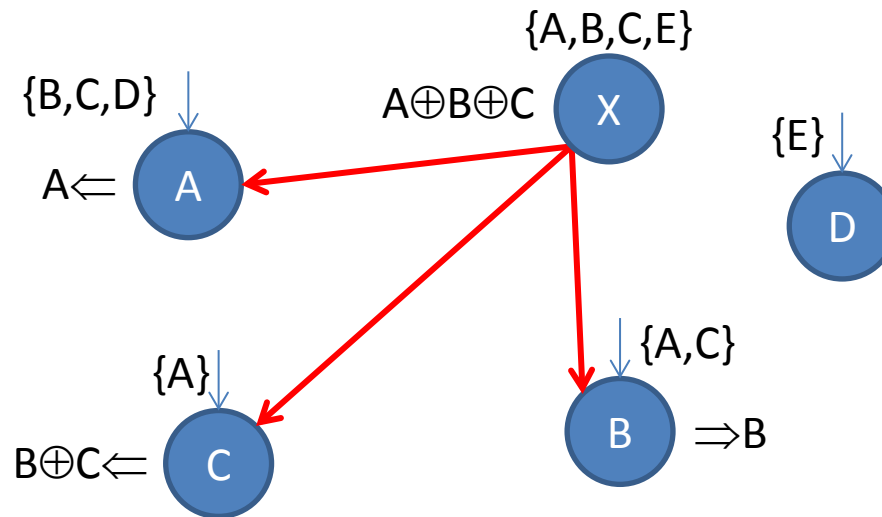
# How I then saw NC and MU-ARQ

- Network Coding (Ahlsvede00)
  - A network with fixed identical capacities on each link.
  - No storage of information
  - Not broadcast-like
  - A system without feedback
  - Through "non-linear mixing", i.e. GF(.), exploiting the network connectivity for increased capacity, or reduced delay
- "Multiuser-ARQ"
  - A network with randomly varying links, packet erasures.
  - Storage of overheard information
  - Broadcast-like
  - A system with feedback
  - Through "non-linear mixing", i.e. GF(.), exploiting packet erasures, feedback, and adaptive coding, for increased capacity, or reduced delay

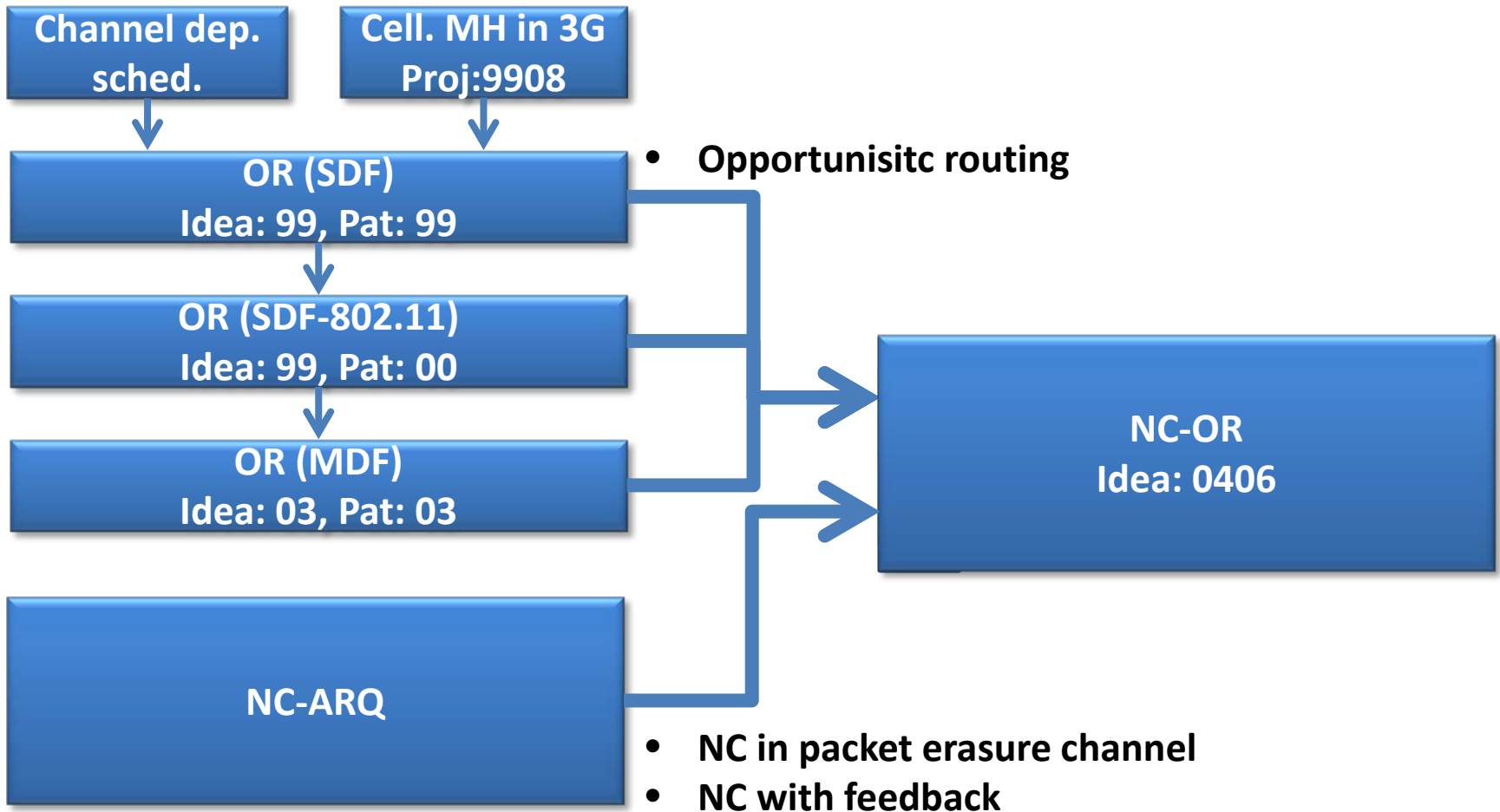


# Summer 2004

- (N)CBR & NC-ARQ were fun.  
What else is possible?
  - NC-Multihop / Ad hoc netw.

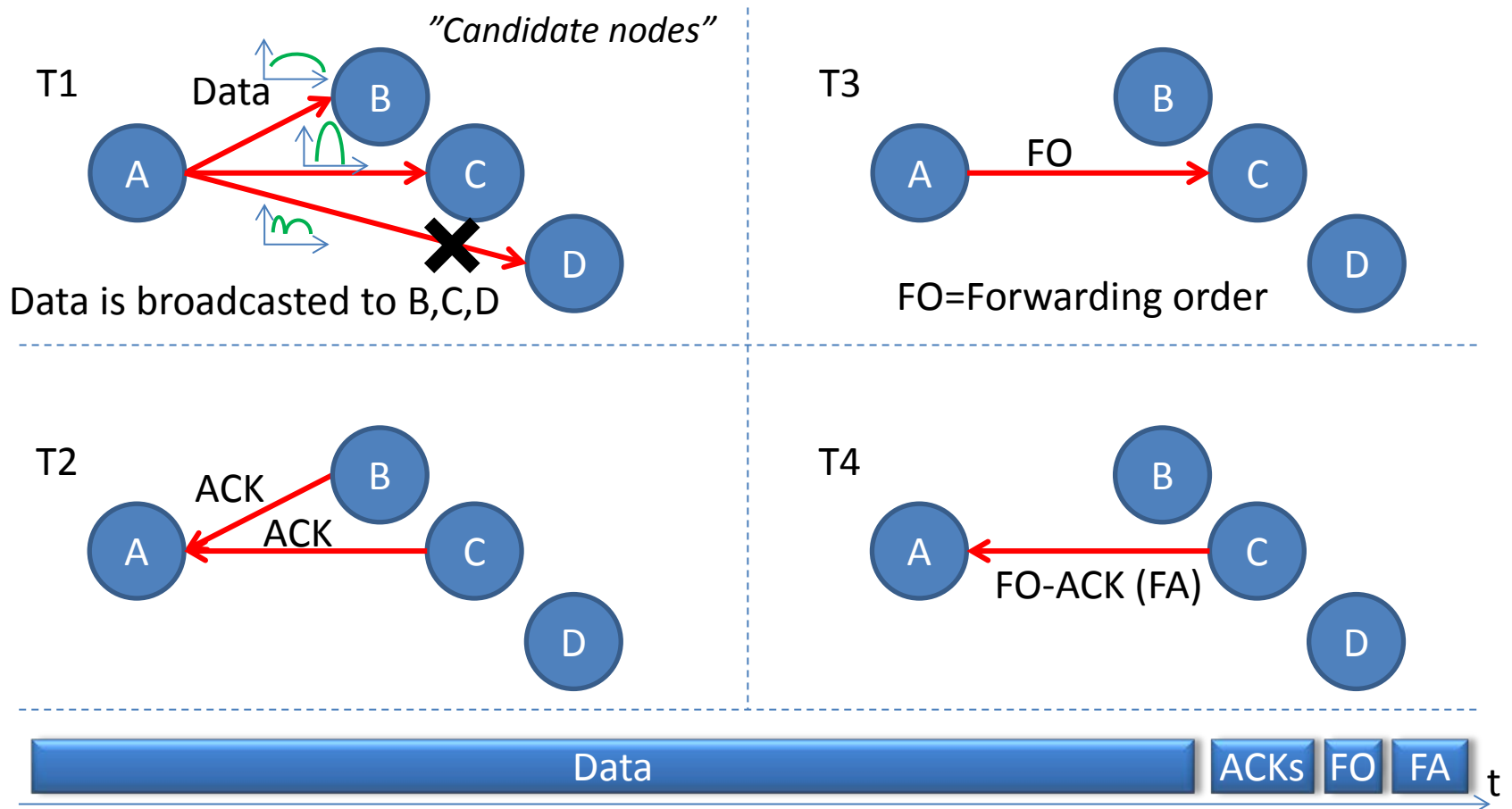


# Why this idea?



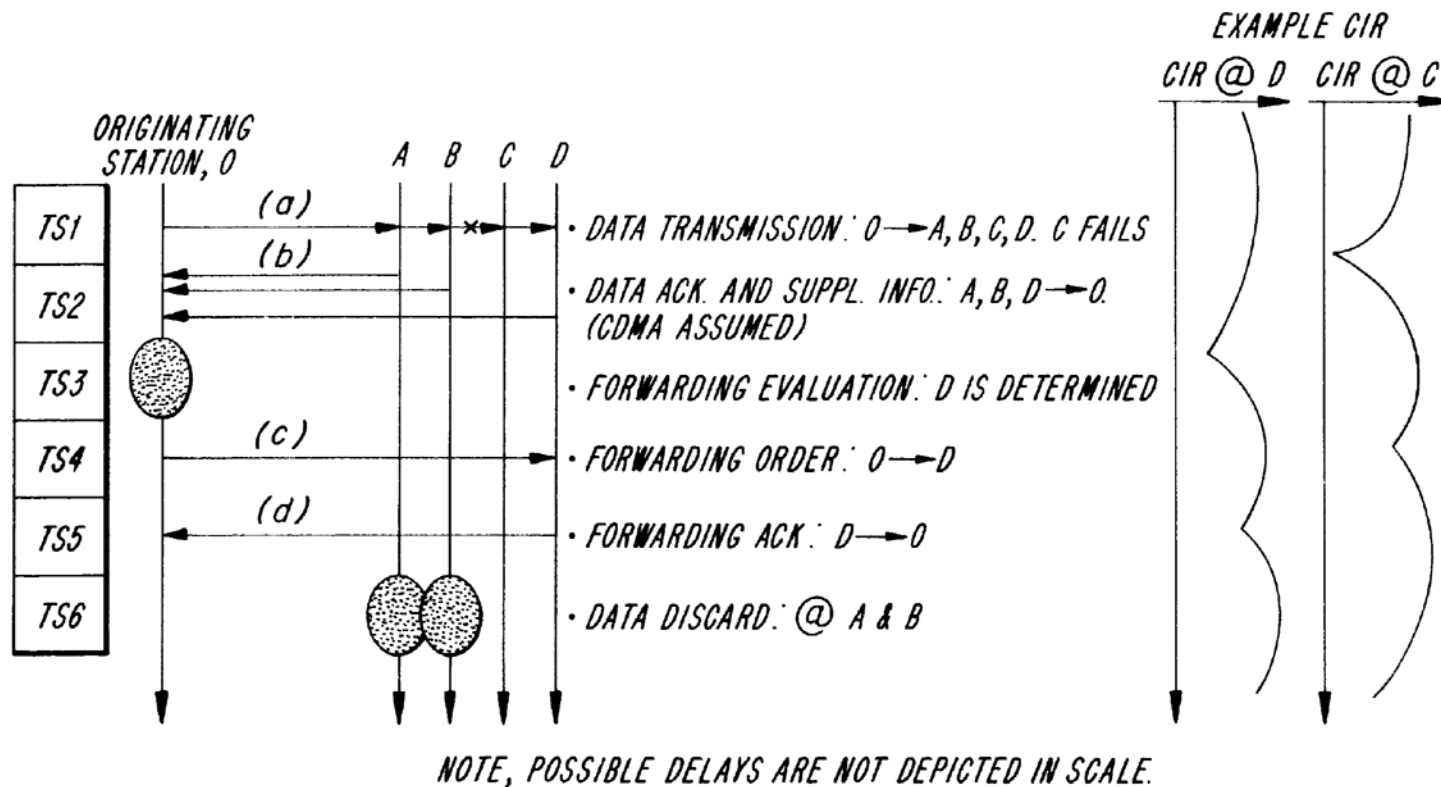
# Opportunistic routing: SDF

- Exploit channel variations + alternative paths!
  - Send data first, then decide route based on success.



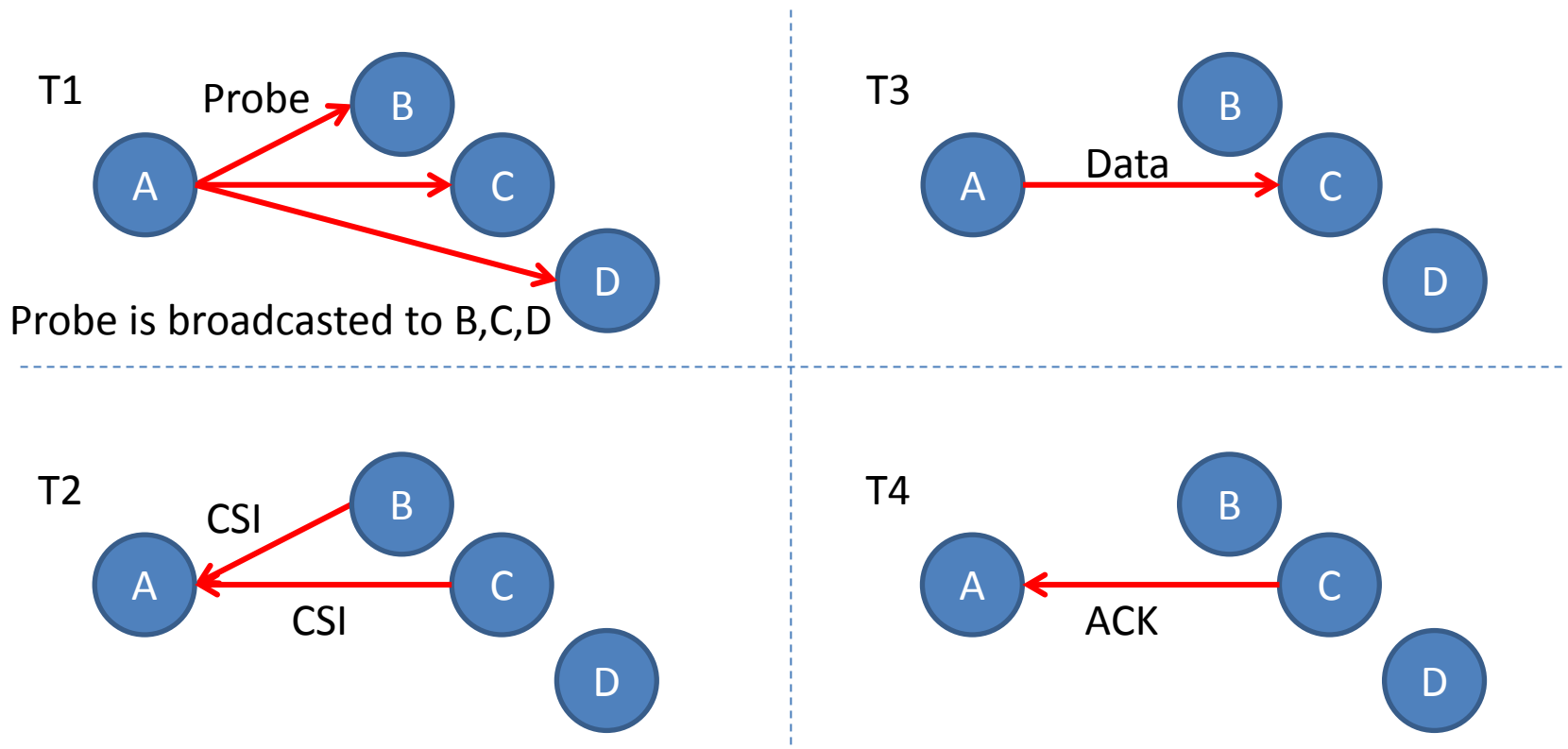
# Opportunistic routing: SDF

- Pat US 6788670 B1, filed 2000-10-27



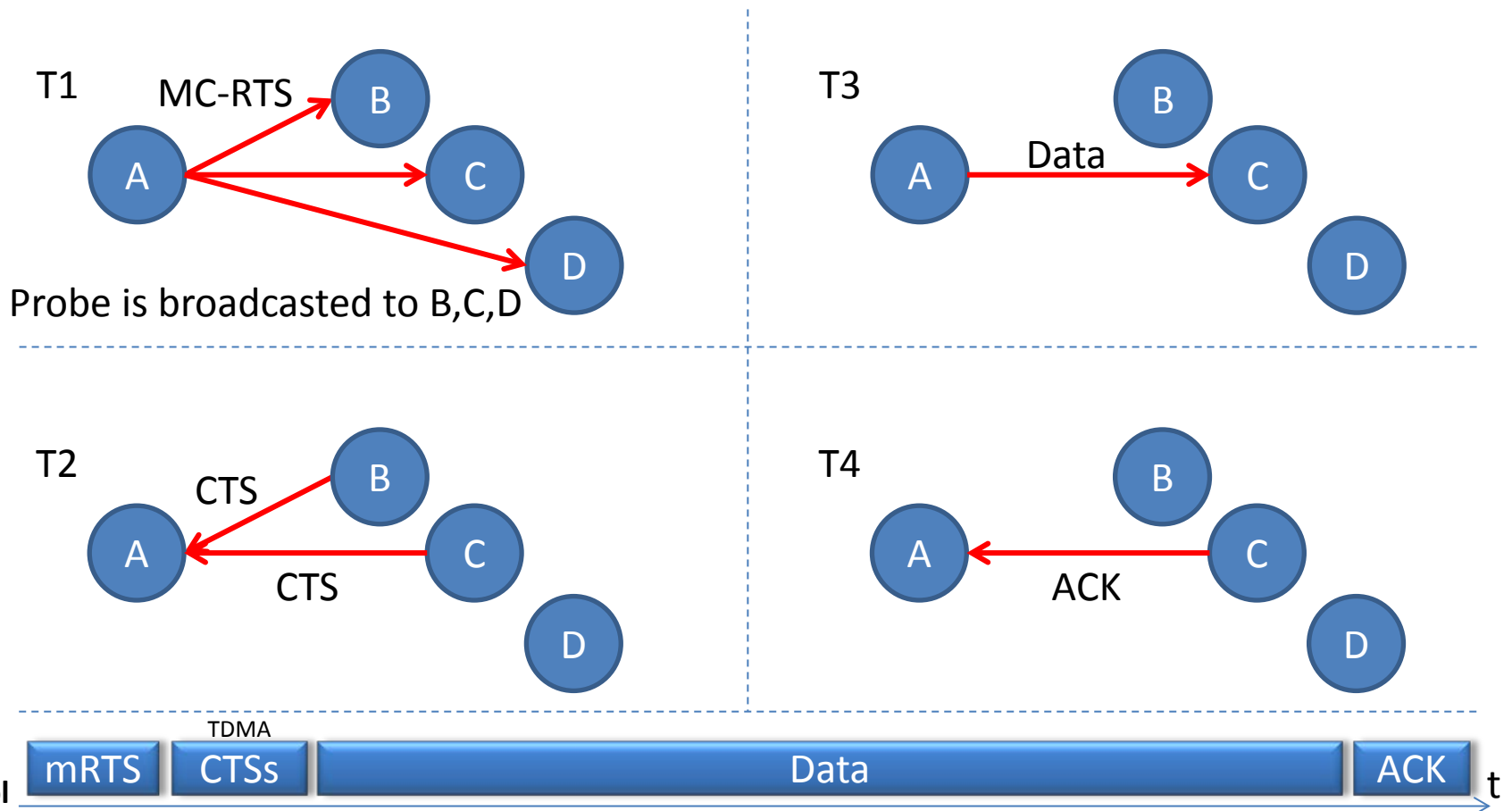
# Opportunistic routing: SDF-802.11

- Exploit channel variations + alternative paths!
  - Probe first, decide route, then send data.



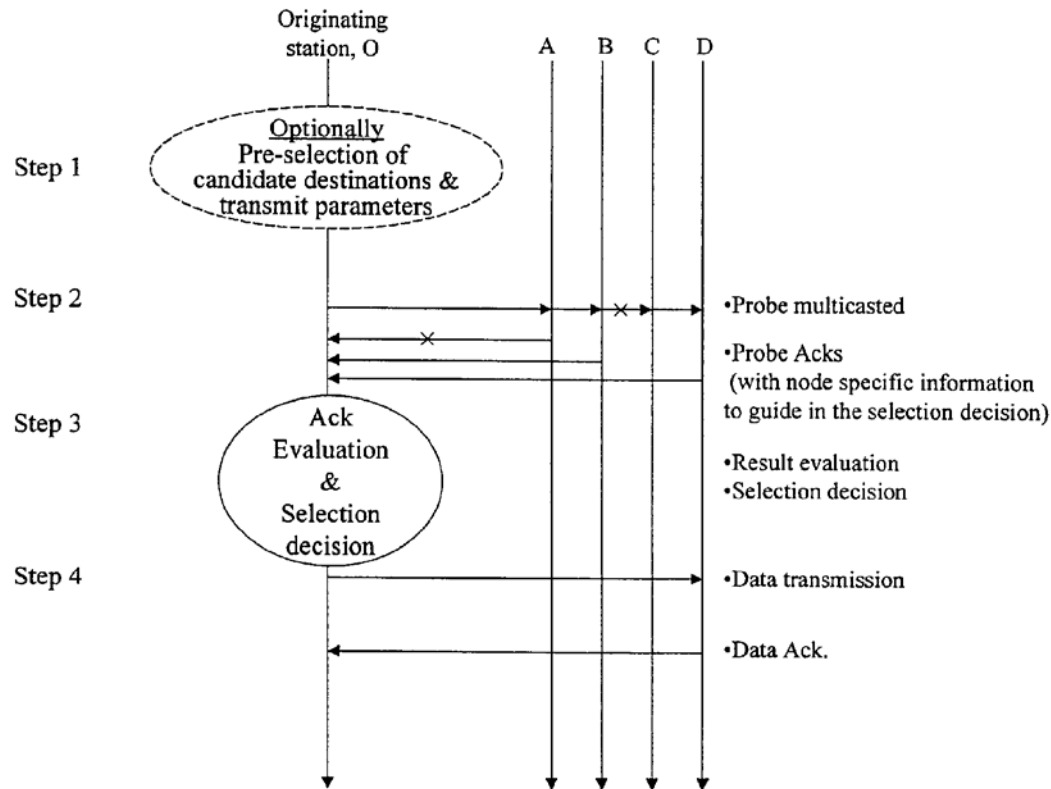
# Opportunistic routing: SDF-802.11

- Exploit channel variations + alternative paths!
  - Probe first, decide route, then send data.



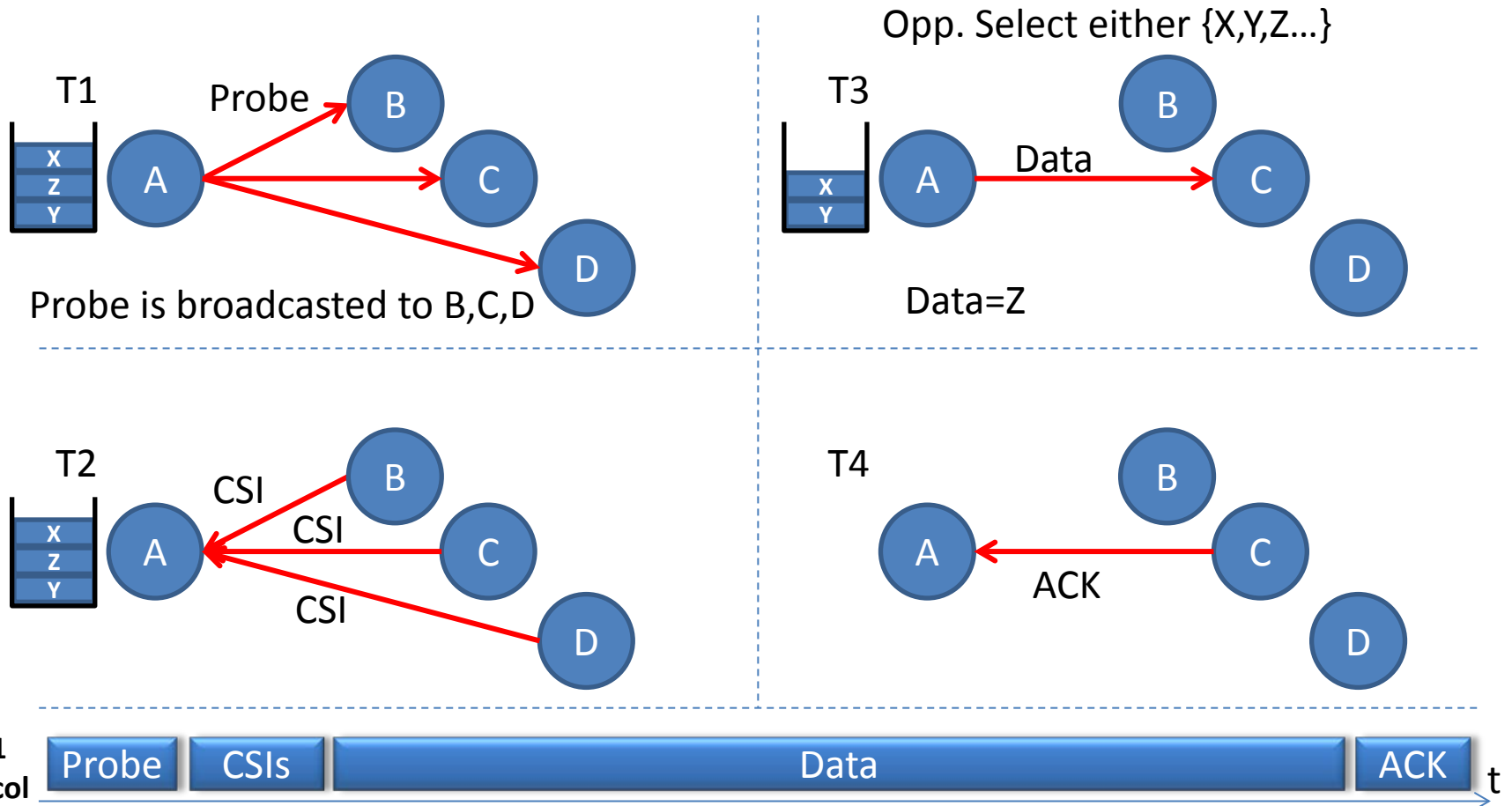
# Opportunistic routing: SDF-802.11

- Pat. US 6798765 B2, filed 2001-10-04



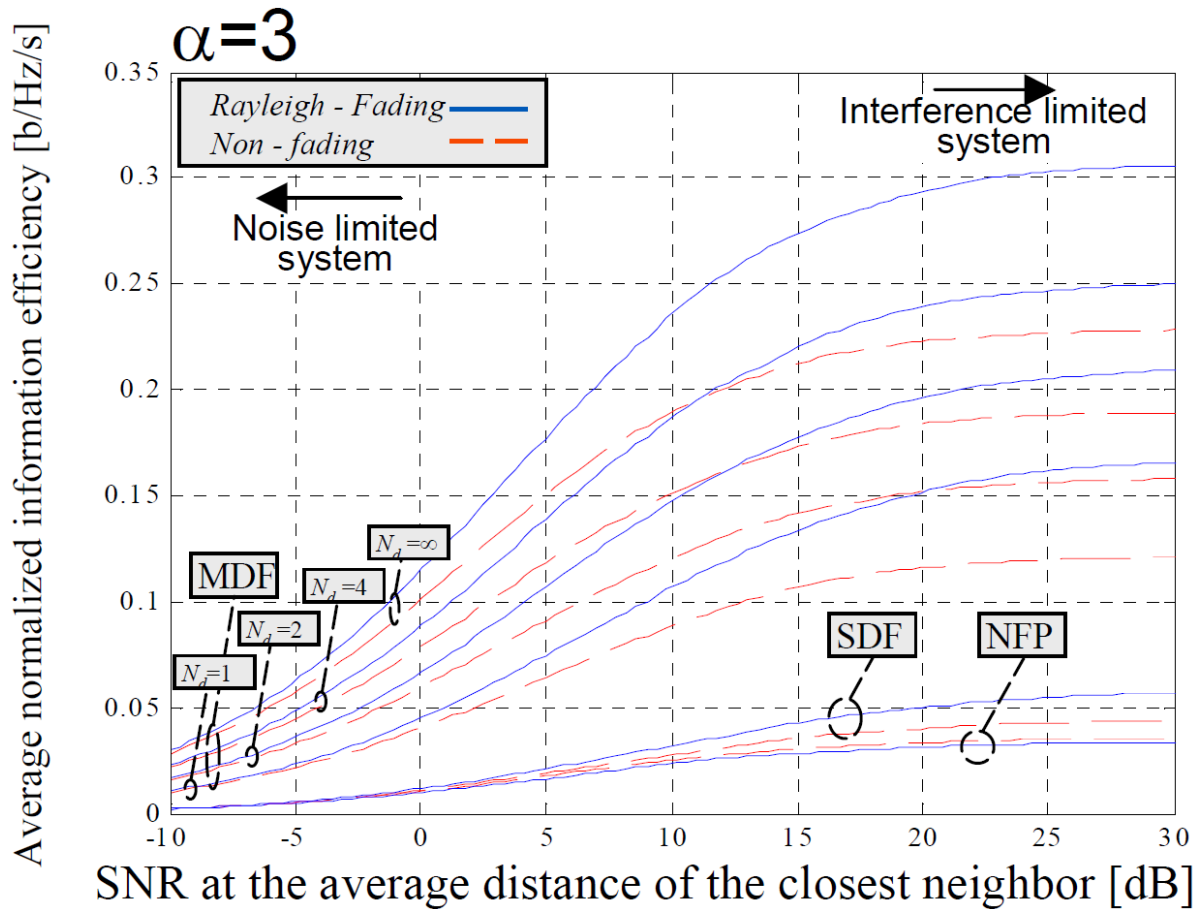
# Opportunistic routing: MDF

- Exploit channel variations, alternative paths, alternative packets!  $\Rightarrow$  x10 Perf.

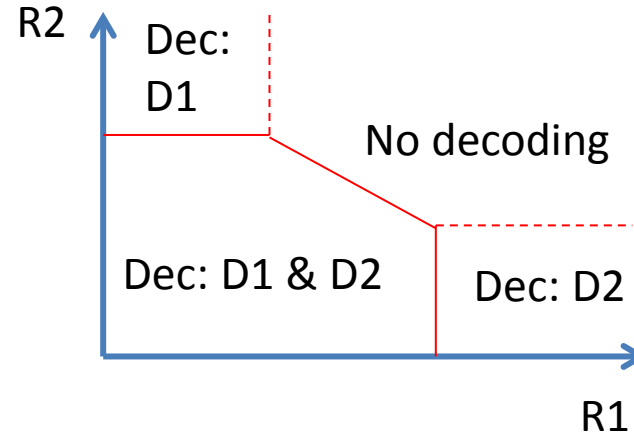
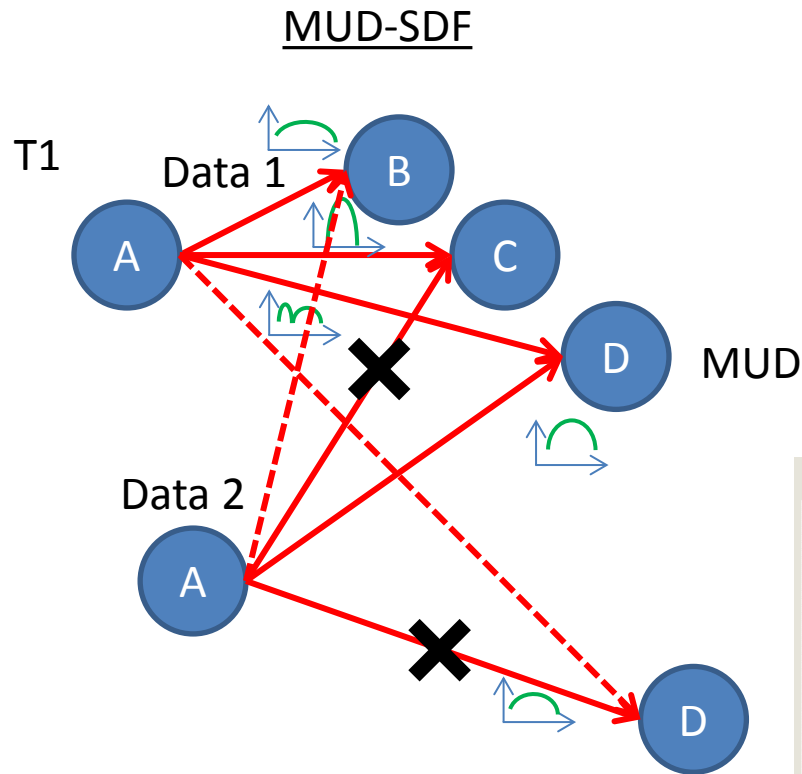




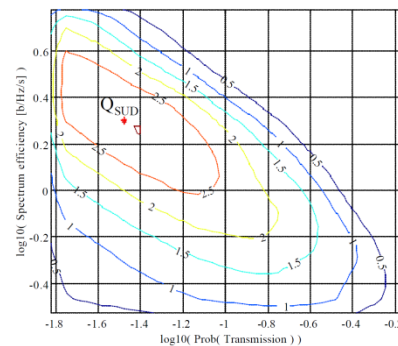
# Performance SDF vs. MDF



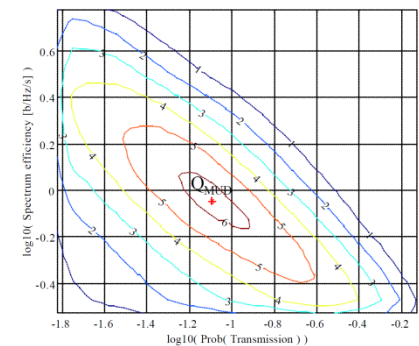
# MUD-enabled OR



Single User Detection - SDF

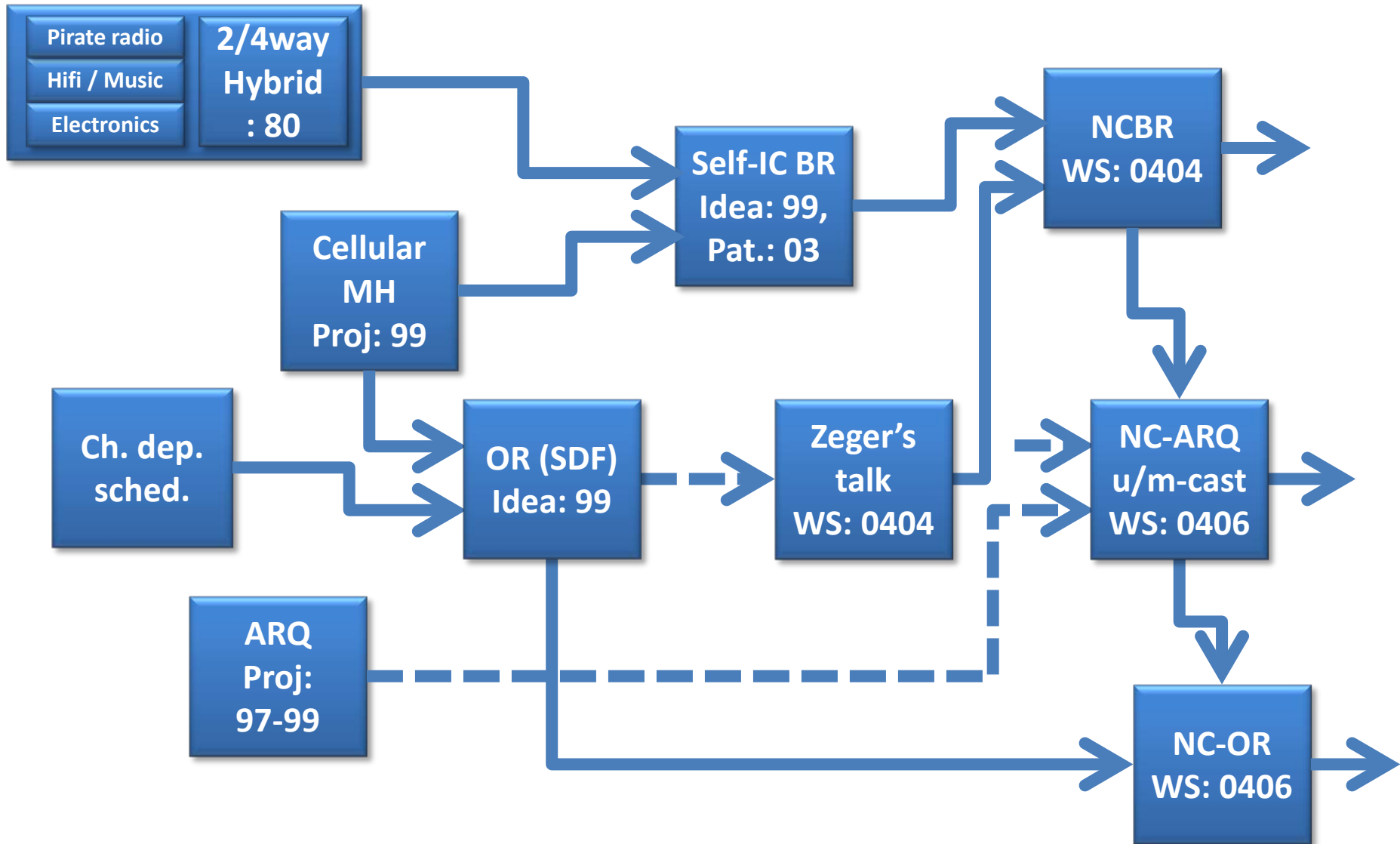


Multi User Detection - SDF



SIC-enabled OR prepared to ADHOC03, but could not be presented due to slow patenting process.

# Some key-events



From 2004 and onwards to the future

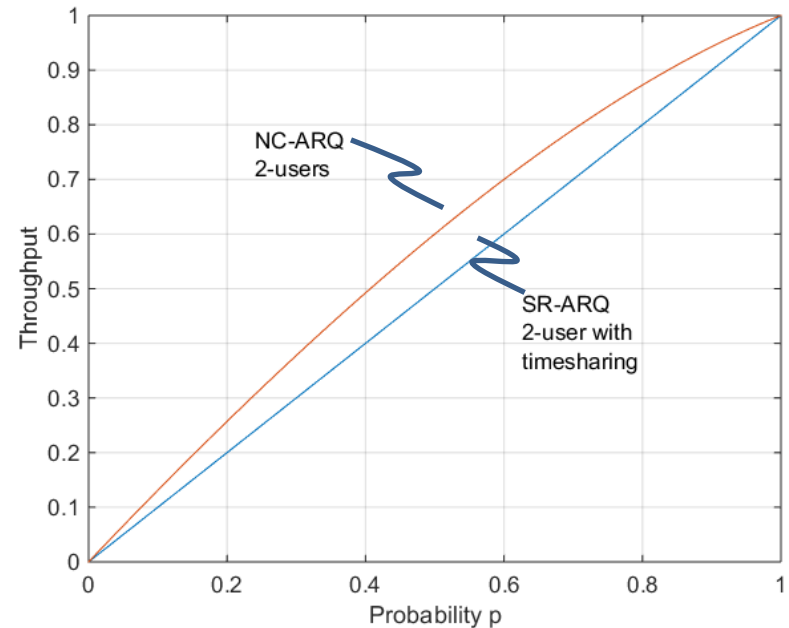
## **PART II**

# How were the NC-ideas received?

- 4G-Proj. IPR WS Oct-04
  - Project leader sceptical!  
*"This will not give very much..."*
  - But, the present project members were enthusiastic
- Patenting the ideas
  - Wrote IvD for i) NCBR and ii) NC-ARQ & NC-OR:
  - Requested immediate prov. filing. Nothing happened!
  - NCBR:
    - "This is coding, thus we need coding experts!". Forwarded to another department.
    - Prio. went ok. 3 months from IvD to provisional filing 0412.
  - NC-ARQ (& NC-OR):
    - "Isn't this Fountain-coding?",
    - "Doesn't this consume more battery?",
    - "This is coding, thus we need coding experts!"
    - "Doesn't this require extra signalling?"
    - "What about power control?"
    - "Doesn't encryption and scrambling becomes impossible?"

# How were the NC-ideas received?

- NC-ARQ (& NC-OR):
  - “Isn’t this Fountain-coding?”
    - No!
    - Different goal, different operation!
  - “Doesn’t this consume more battery?”
    - Is it a showstopper?
  - “This is coding, thus we need coding experts!”
    - This is bit-wise XORing!
  - “Doesn’t encryption and scrambling becomes impossible?”
    - No, why should it?
  - “What about power control?”
    - PC not used in 3G, why an issue here?
  - “Doesn’t this require extra signalling?”
    - Yes, but is it a showstopper?



# NCBR patent, 2004-12

(12) **United States Patent**  
**Larsson et al.** (10) **Patent No.:** **US 7,920,501 B2**  
(45) **Date of Patent:** **Apr. 5, 2011**

(54) **METHOD AND ARRANGEMENT FOR BI-DIRECTIONAL RELAYING IN WIRELESS COMMUNICATION SYSTEMS**

(75) Inventors: **Peter Larsson**, Solna (SE); **Niklas Johansson**, Sollentuna (SE); **Kal-Erik Sunell**, Bromma (SE)

(73) Assignee: **Telefonaktiebolaget LM Ericsson (publ)**, Stockholm (SE)

(\* ) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 941 days.

(21) Appl. No.: **11/794,473**

(22) PCT Filed: **Dec. 22, 2005**

(86) PCT No.: **PCT/SE2005/002042**

§ 371 (e)(1), (2), (4) Date: **Jun. 29, 2007**

(87) PCT Pub. No.: **WO2006/071187**

PCT Pub. Date: **Jul. 6, 2006**

(65) **Prior Publication Data**

US 2009/0268662 A1 Oct. 29, 2009

(30) **Foreign Application Priority Data**

Dec. 30, 2004 (SE) ..... 0403218

(51) **Int. Cl.**  
**H04B 7/14** (2006.01)

(52) **U.S. Cl.** ..... **370/315; 370/352**

(58) **Field of Classification Search** ..... None  
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,596,439 A 1/1997 Dankberg et al.  
2003/0031198 A1\* 2/2003 Currihan et al. .... 370/465  
2004/0114576 A1\* 6/2004 Itoh et al. .... 370/352

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JP 2004-510380 2/2004  
WO WO 97/05711 2/1997  
WO WO 02/27939 4/2002  
WO WO 2004/107693 12/2004

OTHER PUBLICATIONS

International Search Report mailed Jun. 8, 2006.  
International Preliminary Report of Patentability.

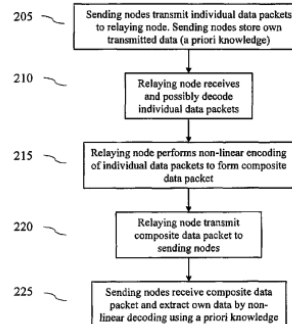
(Continued)

*Primary Examiner* — Erika A Gary  
(74) *Attorney, Agent, or Firm* — Nixon & Vanderhye P.C.

(57) **ABSTRACT**

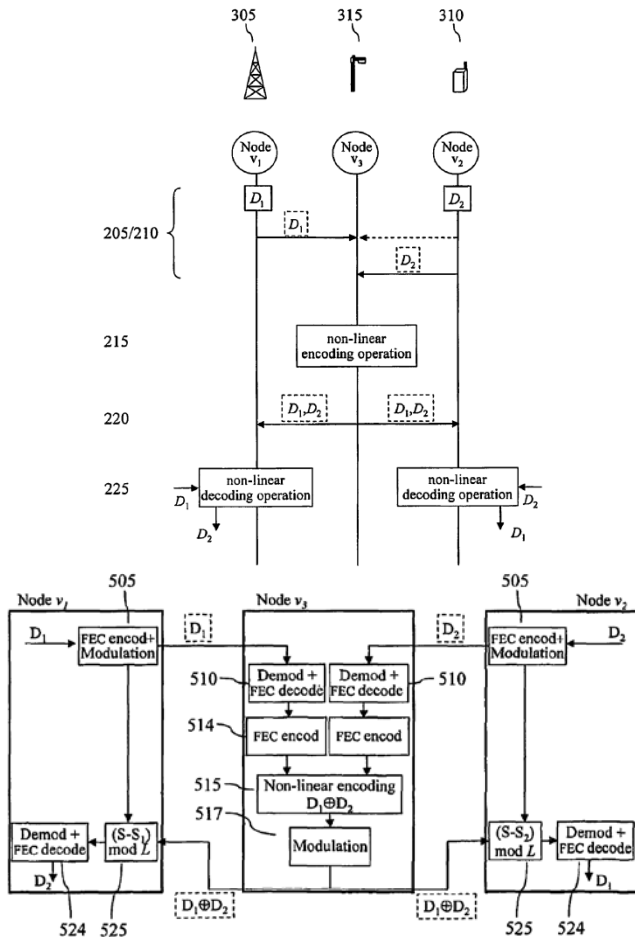
A relaying node is in bidirectional communication with at least a first and a second sending/receiving radio node, and the relaying radio node receives at least a first signal carrying at least first data and a second signal carrying at least second data. The relaying node generates a reduced representation of at least the first and second signal, with a reduced information content as compared to the first and second data, by a joint non-linearly encoding operation, and transmits the reduced representation to at least the first and the second communication node. The first and second sending/receiving node can extract data from the reduced representation by a non-linear decoding operation using stored a priori information.

**52 Claims, 10 Drawing Sheets**

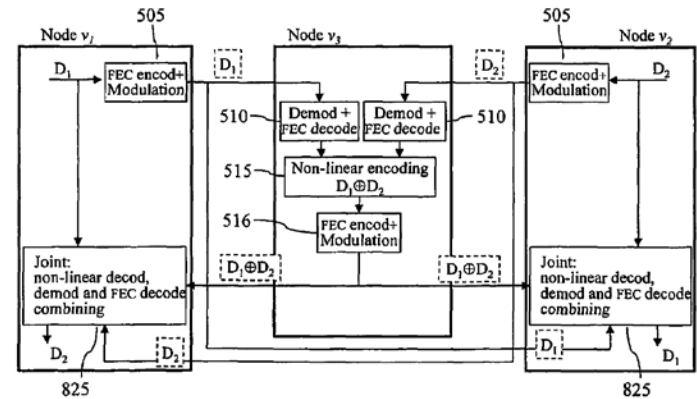


# Some concepts in NCBR patent

- NCBR



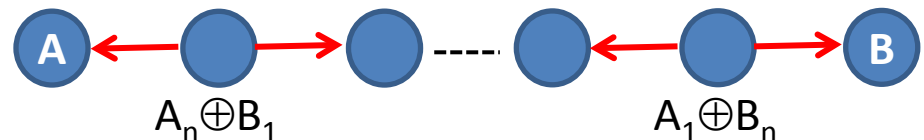
- NC w. soft-combining
  - ML, MRC,



- NC with "lattice coding"

$$(S_2^{(Re)} + S_2^{(Re)}) \bmod L,$$

- Long MH-chain



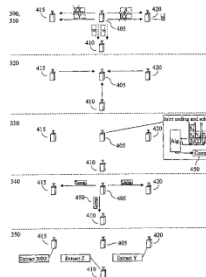


# NC-ARQ/MH patent 2005-07

(12) **United States Patent**  
Larsson et al.

(10) **Patent No.:** US 8,605,642 B2  
(45) **Date of Patent:** Dec. 10, 2013

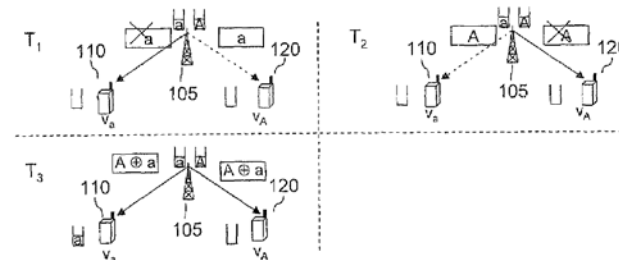
- (54) **METHOD AND ARRANGEMENT FOR CODING AND SCHEDULING IN PACKET DATA COMMUNICATION SYSTEMS**
- (75) Inventors: **Peter Larsson**, Solna (SE); **Kai-Erik Sunell**, Bromma (SE); **Niklas Johan Johansson**, Sollentuna (SE)
- (73) Assignee: **Telefonaktiebolaget L M Ericsson (Publ)**, Stockholm (SE)
- (\*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 1444 days.
- (21) Appl. No.: **11/994,920**
- (22) PCT Filed: **Jul. 7, 2005**
- (86) PCT No.: **PCT/SE2005/001144**  
§ 371 (c)(1), (2), (4) Date: **Jul. 22, 2008**
- (87) PCT Pub. No.: **WO2007/008123**  
PCT Pub. Date: **Jan. 18, 2007**
- (65) **Prior Publication Data**  
US 2009/0147738 A1 Jun. 11, 2009
- (51) **Int. Cl.**  
*H04B 7/14* (2006.01)  
*H04W 4/00* (2009.01)  
*H04W 72/00* (2009.01)  
*H04L 12/54* (2013.01)  
*H04L 1/18* (2006.01)
- (52) **U.S. Cl.**  
USPC ..... 370/315; 370/328; 370/428; 455/24; 455/451; 455/452.1; 714/748
- (58) **Field of Classification Search**  
USPC ..... 370/315, 336, 390, 432, 328, 428; 714/746-751; 455/9, 18, 24, 455/451-452.2
- See application file for complete search history.
- (56) **References Cited**  
U.S. PATENT DOCUMENTS  
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2004/0205105 A1\* 10/2004 Larsson et al. .... 709/200  
(Continued)
- FOREIGN PATENT DOCUMENTS  
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WO WO 02/052771 7/2002
- OTHER PUBLICATIONS  
Jolfiaci, A. "Efficient Block Recovery Schemes for ARQ retransmission strategies" In Personal, Indoor and Mobile Radio Communications, 1994 Wireless Networks-Catch Mobile Future 5<sup>th</sup> IEEE International Symposium on Publication date Sep. 18-23, 1994 vol. 3 on pp. 781-785.  
(Continued)
- Primary Examiner* — Un C Cho  
*Assistant Examiner* — Jeremy Costin
- (57) **ABSTRACT**  
The method and arrangement according to the present invention relates to of scheduling and coding in communication systems utilizing automatic repeat request (ARQ) and/or multihop scheduling and forwarding. According to the inventive method the receiving nodes selectively stores received information, also overheard information, as a priori information and feed back information about their respective stored a priori information to a sending node. The sending node forms composite data packets by jointly encoding and scheduling multiple data packets, which composite data packets are transmitted to receiving nodes. Upon receiving a composite data packet the receiving nodes uses their stored a priori information in the process of extracting data for themselves from the composite data packets.
- 29 Claims, 11 Drawing Sheets**



(12) **United States Patent**  
Larsson et al.

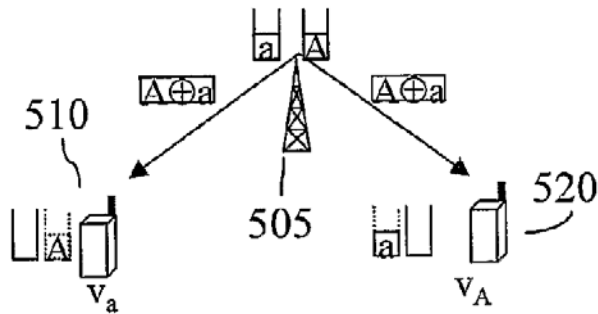
(10) **Patent No.:** US 7,710,908 B2  
(45) **Date of Patent:** May 4, 2010

- (54) **METHOD AND ARRANGEMENT FOR CODING AND SCHEDULING IN A RETRANSMISSION COMMUNICATION SYSTEM**
- (75) Inventors: **Peter Larsson**, Solna (SE); **Niklas Johan Johansson**, Sollentuna (SE)
- (73) Assignee: **Telefonaktiebolaget L M Ericsson (publ)**, Stockholm (SE)
- (\*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.
- (21) Appl. No.: **11/994,942**
- (22) PCT Filed: **May 5, 2006**
- (86) PCT No.: **PCT/SE2006/050109**  
§ 371 (c)(1), (2), (4) Date: **Jul. 22, 2008**
- (87) PCT Pub. No.: **WO2007/008163**  
PCT Pub. Date: **Jan. 18, 2007**
- (65) **Prior Publication Data**  
US 2008/0310409 A1 Dec. 18, 2008
- (50) **Foreign Application Priority Data**  
Jul. 7, 2005 (WO) ..... PCT/SE2005/001144
- (51) **Int. Cl.**  
*H04H 20/71* (2008.01)
- (52) **U.S. Cl.** ..... 370/312; 370/395.4; 370/474; 714/748
- (58) **Field of Classification Search** ..... None  
See application file for complete search history.
- (56) **References Cited**  
U.S. PATENT DOCUMENTS  
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(Continued)
- FOREIGN PATENT DOCUMENTS  
WO WO2007/008123 1/2007
- OTHER PUBLICATIONS  
WO 2006/085801. Johansson et al. Quality-based data scheduling. Aug. 17, 2006.\*  
(Continued)
- Primary Examiner* — Salman Ahmed  
*Assistant Examiner* — Peter Chau  
(74) *Attorney, Agent, or Firm* — Roger S. Burleigh
- (57) **ABSTRACT**  
A sending node (405) is adapted for communication with several receiving nodes (410, 420) by transmitting information in the form of a regular data packet to at least one intended receiving nodes, said sending node comprising— means to receive, identify and store a priori information in feedback from receiving nodes (410, 420); —means (905) for forming a composite data packet from at least two regular data packets, said means arranged to use a priori information from said a priori information storage module (910) and to determine which multiple individual data packets to retrieve from a buffer module (920) for use in the composite data packet, said means being arranged to form a composite data packet from which the intended receiving node for each of the at least two regular packets can decode the composite packet to obtain at least one packet intended for it.
- 31 Claims, 9 Drawing Sheets**

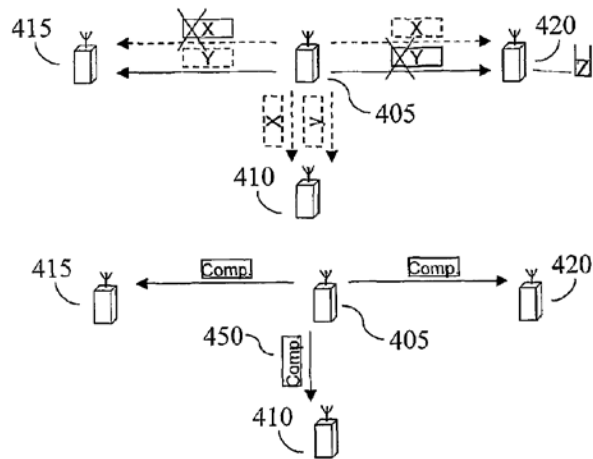


# Some concepts in NC-ARQ/MH patent

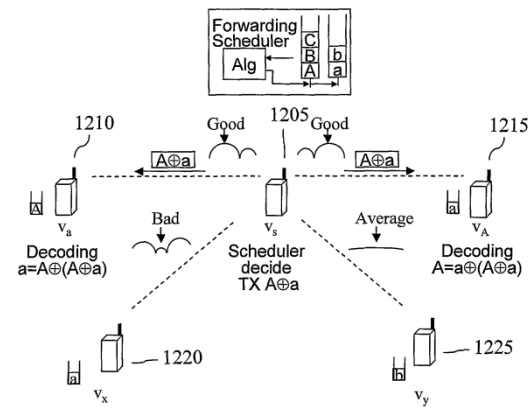
- NC-ARQ



- NC-Opp. routing



- NC Opp. Scheduling



- NC with "lattice coding" on soft bits

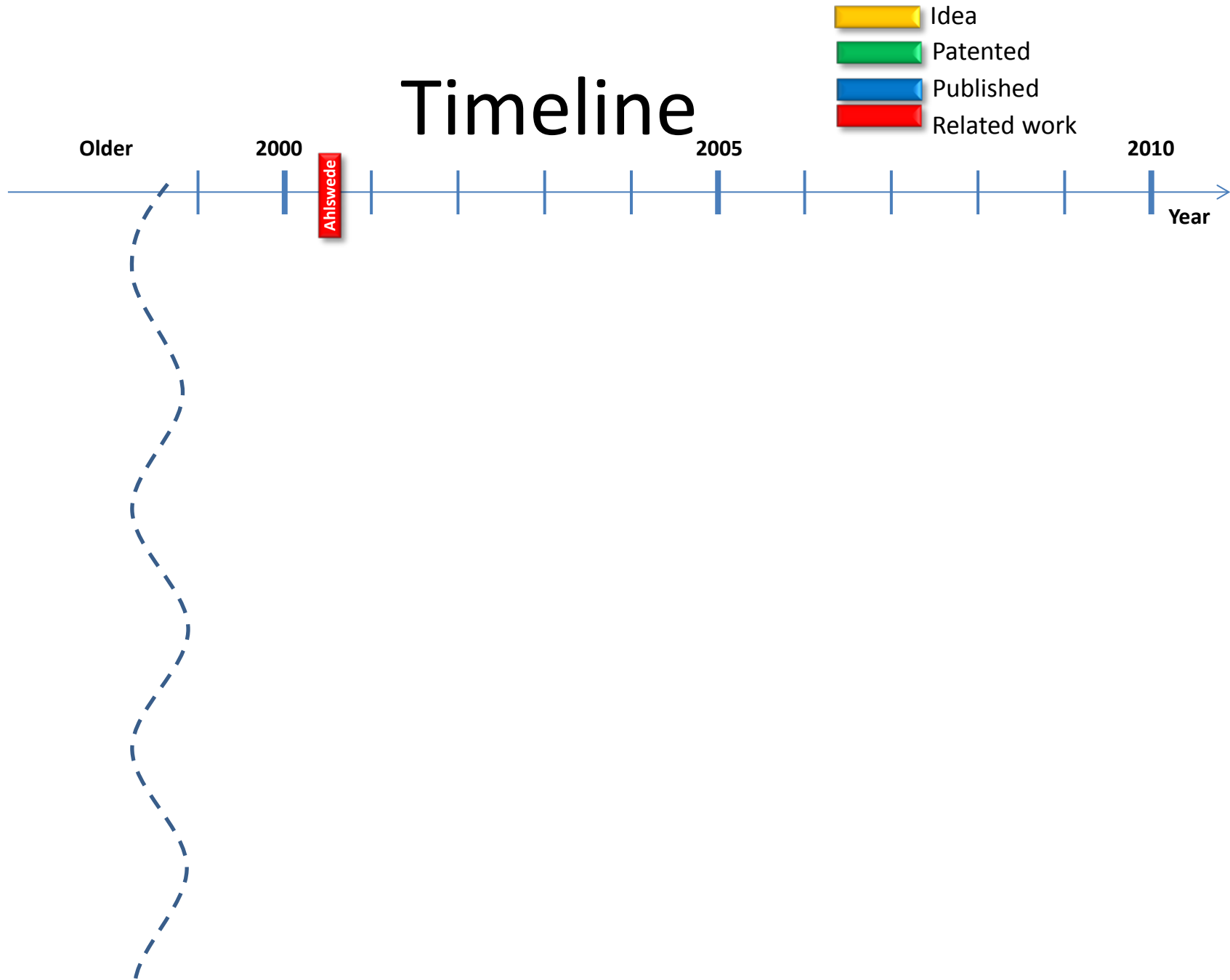
$$(S_2^{(Re)} + S_2^{(Re)}) \bmod L,$$

Area	Title	Slogan	Conf name / Patent #	Date of filing/conf.	Concepts introduced
ANC	Interference Cancellation In Wireless Relaying Networks		WO 2004/102891, PCT/SE2004/000633. EP 1625697 B1 , US 73386930 B2, CN 1826761 B	030515	<ul style="list-style-type: none"> <li>Self-IC for multihop chain (MH)</li> <li>SIC for bidirectional relaying (BR)</li> <li>SIC for adhoc / MH network</li> <li>SIC for BR with MUD</li> <li>2- and 3-phases SIC for BR.</li> </ul>
	"Method for forwarding in multihop networks"	Selection diversity forwarding (SDF)	WO 2002/035779, PCT/SE2001/002342. EP1329062 B1, US 6788670 B1, CN 1197309 C	001027	<ul style="list-style-type: none"> <li>OR with retrospective decision</li> <li>(ExOR06 suggests the same main idea)</li> </ul>
OR	"Selection Diversity Forwarding"	SDF	1st Scandinavian Workshop on Ad Hoc Networks (ADHOC'01), Stockholm, Sweden.	0103	<ul style="list-style-type: none"> <li>Perf. evaluation of SDF</li> </ul>
	Method for forwarding in multi-hop networks	SDF -802.11	US 6798765 B2	011004	<ul style="list-style-type: none"> <li>OR with probe. Aimed for 802.11</li> </ul>
	"Selection diversity forwarding in a multihop packet radio network with fading channel and capture,"	SDF	ACM MobiHoc, 2001, pp. 279–282.	011004	<ul style="list-style-type: none"> <li>OR,</li> <li>OR with retrospective decision</li> </ul>
	P. Larsson, "Selection diversity forwarding in a multihop packet radio network with fading channel and capture,"		in ACM's MC2R ,Vol. 5, No. 4, pp. 47-54, 2001 (Invited paper)	0112	
	Multi-user diversity forwarding	MDF	WO 2004/091155, CT/SE2004/000385. EP 1616412 B1, US 7545765 B2, DE 602004010638 T2	030411	<ul style="list-style-type: none"> <li>OR with probe and opportunistic selection of packet to send</li> </ul>
	Contention-Based Forwarding With Integrated Multi-User Detection Capability		EP 1616411 B1, US 7464166 B2, CN 100583809 C, CA 2521450 C, DE 602004010090 T2	030411	<ul style="list-style-type: none"> <li>MUD-OR</li> </ul>
	"Cost Determination In A Multihop Network""	"Routing Cost Determination for Opportunistic Routing"	WO 2005/064864", PCT/EP2004/053191. EP 1704687 B1, US 7729260 B2		<ul style="list-style-type: none"> <li>(icapeople.epfl.ch/grossglauser/Papers/al_lerton07.pdf suggests the same main idea)</li> </ul>
	"Verification and Extension of Selection Diversity Forwarding in an End-to-End Scenario and Incorporating Multi User Information Theory,"	SDF with MUD	3rd Swedish Workshop on Wireless Ad-hoc Networks, Stockholm, ,Sweden.	030507	<ul style="list-style-type: none"> <li>MUD-OR</li> </ul>
	"Method And System Of Communications"	Multiuser Diversity Forwarding (MDF)	WO 2006/041403, PCT/SE2005/001525	041013	<ul style="list-style-type: none"> <li>OR with probe and opportunistic selection of packet to send</li> </ul>
	"Method And Apparatus For Routing Packets"	OR over Multi Radio Access Technologies"	US 8139587 B2	041111	<ul style="list-style-type: none"> <li>OR over multi-RAT</li> </ul>
Multiuser Diversity Forwarding (MDF) in Multihop Packet Radio Networks with Channel Fading	MDF	ADHOC03	0305		
"Multiuser diversity forwarding in multihop packet radio networks,"		WCNC05	0503		

Area	Title	Slogan	Conf name / Patent #	Date of filing/conf.	Concepts introduced
NCBR	“Method And Arrangement For Bi-Directional Relaying In Wireless Comm. Systems”	(N)CBR	WO 2006/071187, PCT/SE2005/002042 US7920501 B2	041230	<ul style="list-style-type: none"> <li>NC bidirectional Relaying (NCBR)</li> </ul>
	“Coded Bi-directional Relaying”	(N)CBR	5th Scandinavian Workshop on Ad Hoc Networks (ADHOC’05), Stockholm, Sweden,	0505	<ul style="list-style-type: none"> <li>NCBR</li> </ul>
	“Coded Bi-directional Relaying”		Communication Letters	Submitted spring 05, but (weirdly) rejected	
	“Coded Bi-directional Relaying”	(N)CBR	VTCSpring06	0605	<ul style="list-style-type: none"> <li>NCBR</li> </ul>
				Winner report contribution D3.2	
	“A multiplicative and constant modulus signal based network coding method applied to coded bi-directional relaying”		VTCSpring08	0805	<ul style="list-style-type: none"> <li>NC with PSK signals on phy-layer</li> <li>ARQ for NCBR</li> </ul>
NC-ARQ MC	“Method And Arrangement For Coding And Scheduling In Packet Data Communication Systems”,	k- to fully-reliable NC-multicast-ARQ	WO 2007/008162, PCT/SE2006/050107	060505	<ul style="list-style-type: none"> <li>Multicast-ARQ for k-out-of –K nodes receiving</li> </ul>
	“Reliable Multicast With Linearly Independent Data Packet Coding”,	Optimal Multicast NC-ARQ	WO 2008/066421, PCT/SE2006/001368	061129	<ul style="list-style-type: none"> <li>Optimal throughput Multicast ARQ</li> <li>Introduces sufficient field size</li> <li>Propose to use guaranteed linearly independent NC packets for each K user for esch transmission</li> <li>(“ARQ for NC” 08 suggests the same main idea)</li> </ul>
	“Multicast multiuser-ARQ”	Optimal Multicast NC-ARQ	WCNC2008, Las Vegas, USA	0804	<ul style="list-style-type: none"> <li>Optimal throughput Multicast ARQ</li> <li>Introduces sufficient field size</li> <li>Propose to use guaranteed linearly independent NC packets for each K user for esch transmission</li> </ul>
NCOR	Method And Arrangement For Coding And Scheduling In Packet Data Communication Systems		WO 2007/008123, PCT/SE2005/001144. EP 1900136 B1, US 8605642 B2, CA 2613655 C	050707	<ul style="list-style-type: none"> <li>NC-OR and NC-ARQ</li> <li>“Lattice based NC”,</li> <li>“Opportunistic Network Coding.” i.e. channel dep. Sched. with NC.</li> <li>(COPE 07 does the same thing)</li> </ul>

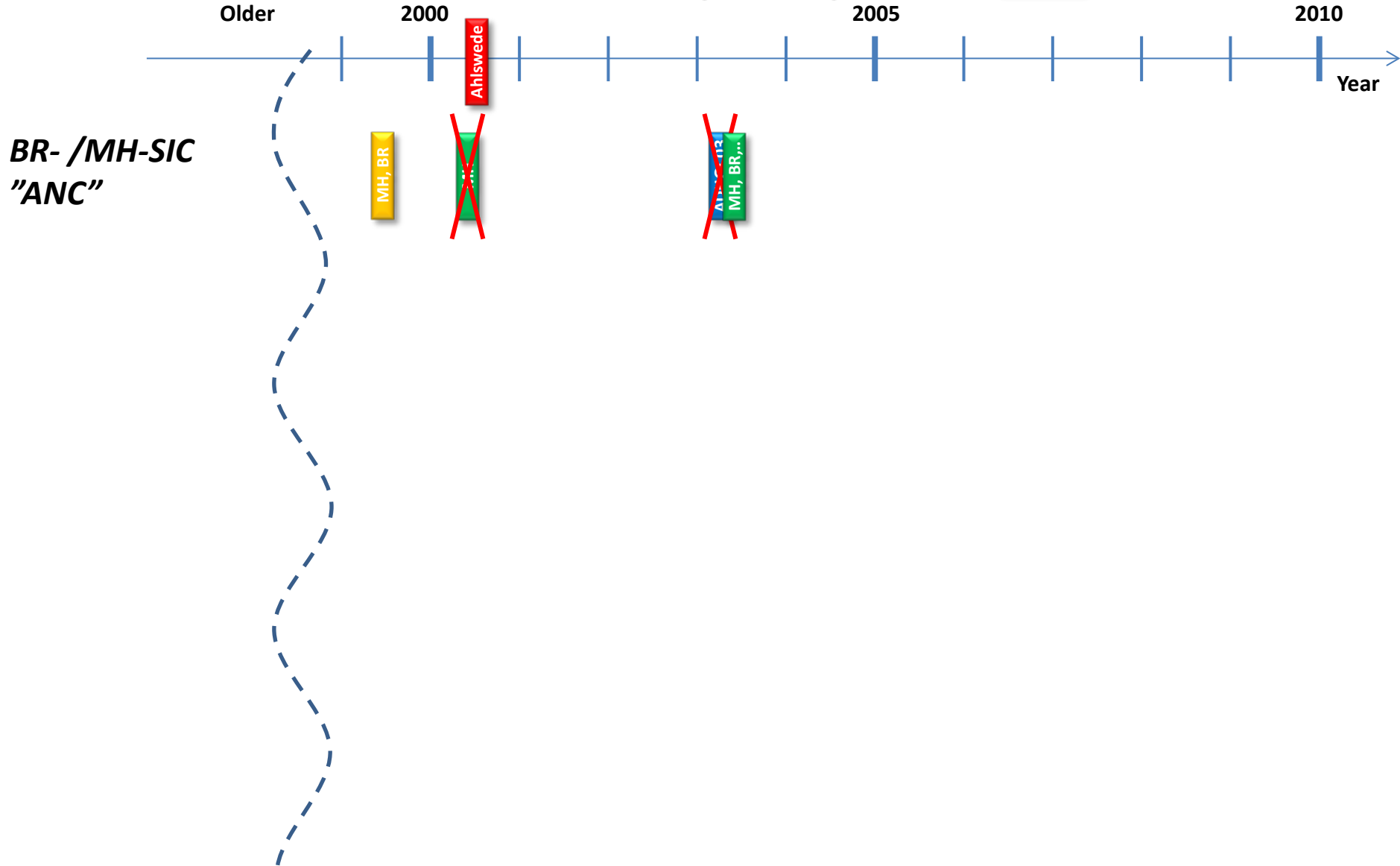
Area	Title	Slogan	Conf name / Patent #	Date of filing/conf.	Concepts introduced
<b>NC-ARQ UC</b>	Method And Arrangement For Coding And Scheduling In Packet Data Communication Systems	MU-ARQ	WO 2007/008123, PCT/SE2005/001144. EP 1900136 B1, US 8605642 B2, CA 2613655 C	050707	
	" Multi-User ARQ"	MU-ARQ	VTCSpring06	0605	<ul style="list-style-type: none"> <li>• NC-ARQ for unicast</li> <li>• Performance Analysis for K users</li> <li>• Optimal scheme for K=2, lower bound for K&gt;2.</li> </ul>
	"Analysis of Multi-User ARQ with Multiple Unicast Flows under Non-iid Reception Probabilities,"	MU-ARQ	WCNC07	0703	<ul style="list-style-type: none"> <li>• Analysis of NC-ARQ with non-identical RX probabilities.</li> </ul>
	"Analysis of Network Coded HARQ for Multiple Unicast Flows",		ICC2010, Cape town, South Africa	1006	<ul style="list-style-type: none"> <li>• Analysis of NC-HARQ (RR and IR)</li> </ul>
	"Multi-layer Network Coded ARQ for multiple unicast flows"		SWE-CTW, pp. 13 - 18, Lund, Oct. 2012.	1210	<ul style="list-style-type: none"> <li>• Joint NC, superposition coding, and ARQ</li> </ul>
	"Analysis of Network Coded HARQ for Multiple Unicast Flows"		IEEE Trans. on Commun., vol.61, no.2, pp.722--732,	1302	<ul style="list-style-type: none"> <li>• Analysis of NC-HARQ (RR and IR)</li> <li>• Extended non-NC phase</li> </ul>
<b>Other NC</b>	"Method And Arrangement For Coding And Scheduling In A Retransmission Communication System"	Optimal NC packet	WO 2007/008163, PCT/SE2006/050109	060505	<ul style="list-style-type: none"> <li>• Design of optimal NC packet for K users</li> </ul>
	"Exchange Of Information In A Communication Network",	All-to-all NC	WO 2008/069713, PCT/SE2006/050536	061204	<ul style="list-style-type: none"> <li>• All-to-all NC in one-hop Ad hoc netw. distributing content-files</li> </ul>
	"Network Coding Based On Soft Feedback"		WO 2008/108700, PCT/SE2007/050932	070306	<ul style="list-style-type: none"> <li>• NC and scheduling based on quality of past receptions at users.</li> </ul>
	"Improved Retransmissions In A Wireless Communications System"		06.03.2007, WO 2008/108708, PCT/SE2008/000181		<ul style="list-style-type: none"> <li>• NC and forwarding in relay network</li> </ul>
	"Advanced Downlink Macrodiversity Operation"		WO 2009/070068, PCT/SE2007/001075	071203	<ul style="list-style-type: none"> <li>• Network coded macrodiversity</li> </ul>
	"Multiplicative Network Coding"	PSK-NC	WO 2009/041884, PCT/SE2008/050861 US8792539	070927	<ul style="list-style-type: none"> <li>• Network coding with PSK</li> </ul>

# Timeline



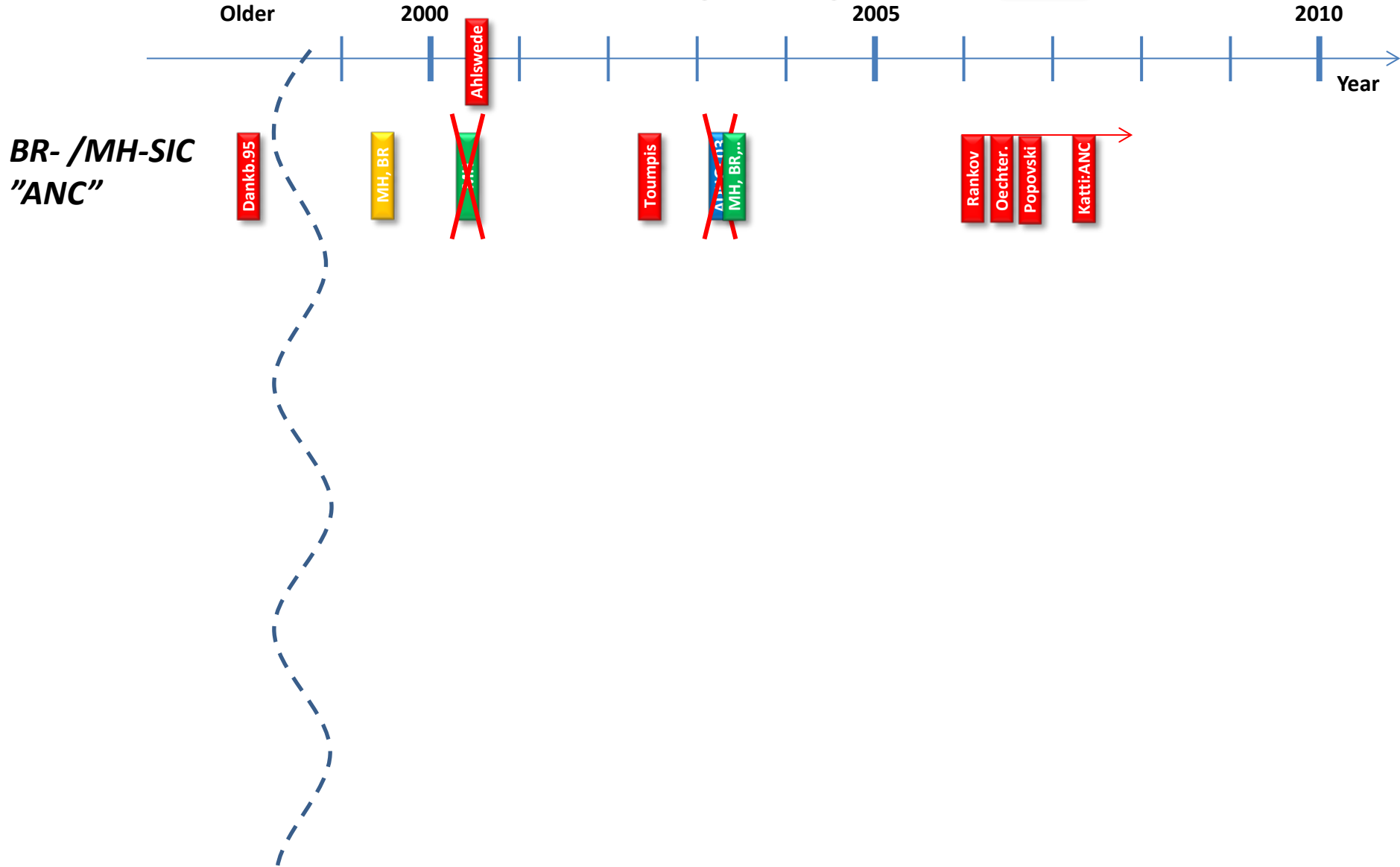
# Timeline

-  Idea
-  Patented
-  Published
-  Related work



# Timeline

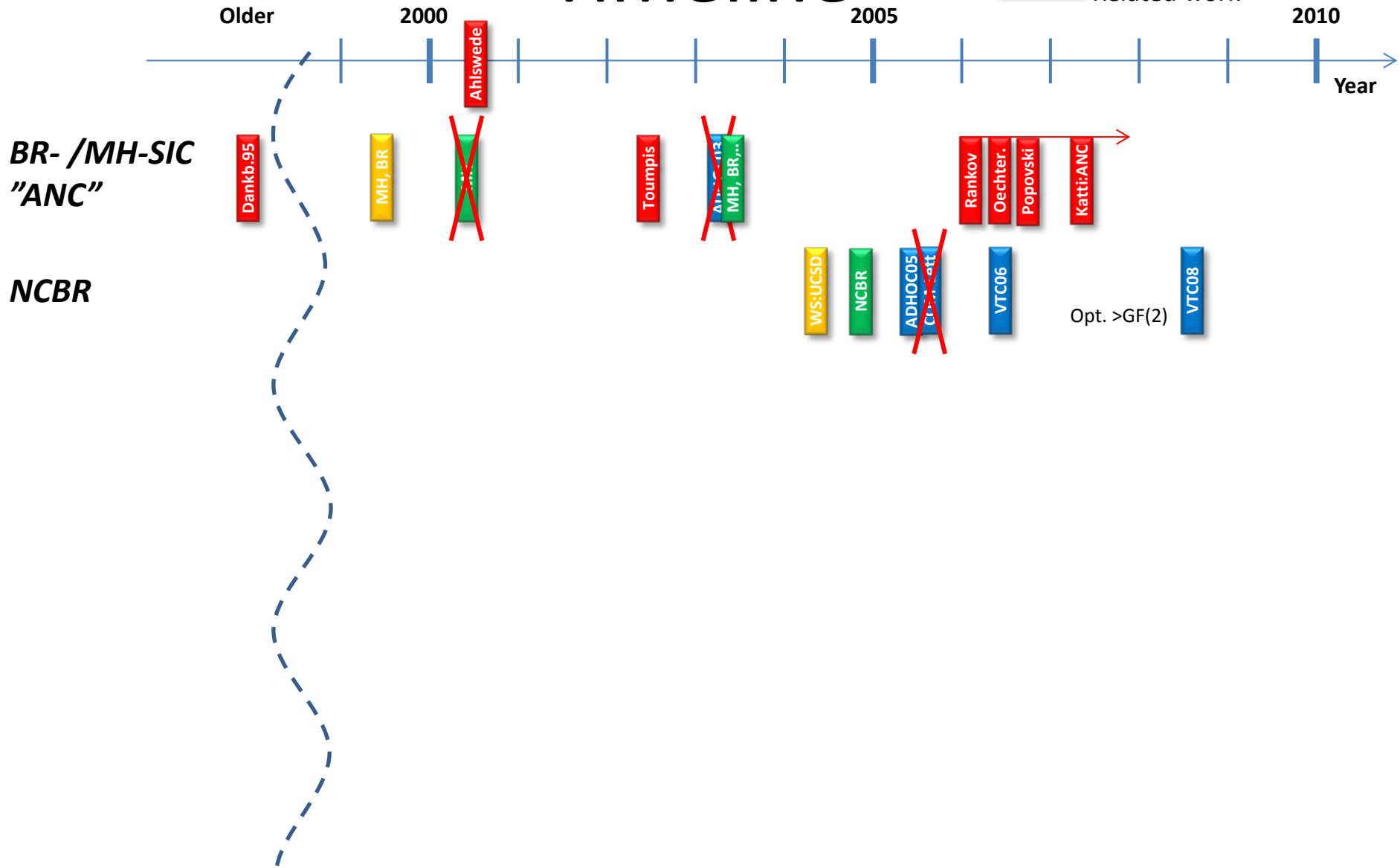
- Idea
- Patented
- Published
- Related work





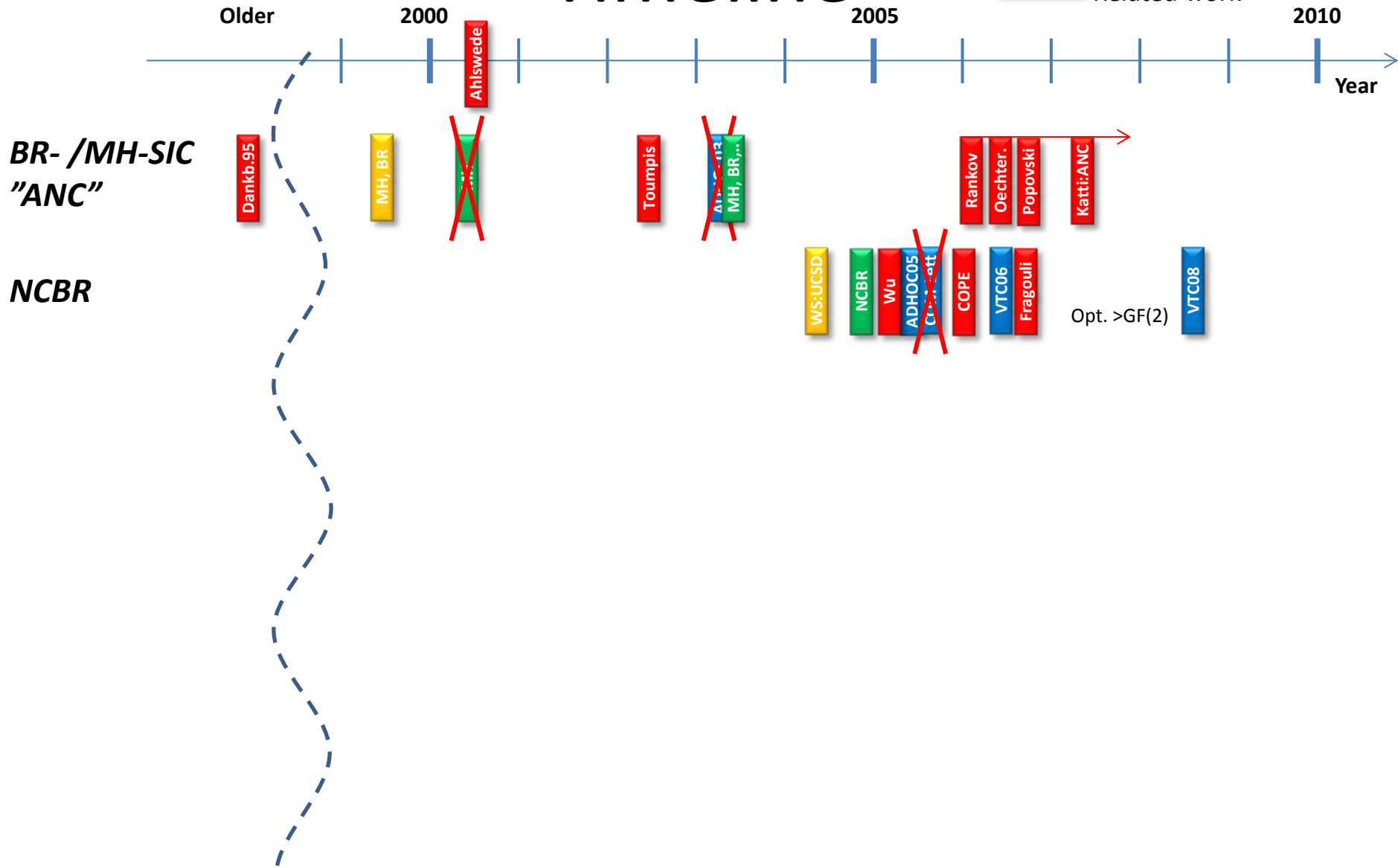
# Timeline

- Idea
- Patented
- Published
- Related work



# Timeline

- Idea
- Patented
- Published
- Related work



# NCBR vs. The Microsoft scheme

Title: **Coded Bi-directional Relaying**

Peter Larsson, Niklas Johansson, Kai-Erik Sunell  
Ericsson Research

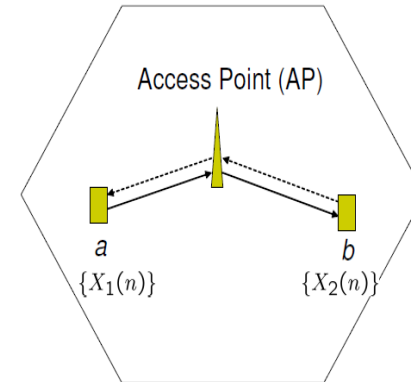
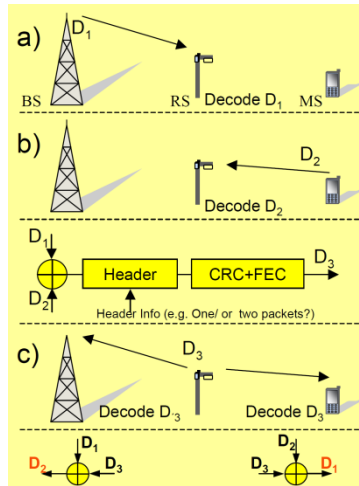
Information Exchange in Wireless Networks  
with Network Coding and Physical-layer Broadcast

Yunnan Wu  
Dept. of Electrical Engineering,  
Princeton University,

Philip A. Chou  
Microsoft Research,  
One Microsoft Way,

Sun-Yuan Kung  
Dept. of Electrical Engineering,  
Princeton University,

Scenario:



Analysis: Wireless channel model  
Sum-capacity in AWGN

Graph model  
Discussion

When? ADHOC'05: 050503  
Patent: 051230  
Presentation: 0409

CISS: 050318  
Report: 0408 ?

# MS-Report

## Information Exchange in Wireless Networks with Network Coding and Physical-layer Broadcast

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## Information Exchange in Wireless Networks with Network Coding and Physical-layer Broadcast

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*Abstract*—We show that mutual exchange of independent information between two nodes in a wireless network can be efficiently performed by exploiting network coding and the physical-layer broadcast property offered by the wireless medium. The proposed approach improves upon conventional solutions that separate the processing of the two unicast sessions, corresponding to information transfer along one direction and the opposite direction. We propose a distributed scheme that obviates the need for synchronization and is robust to random packet loss and delay, and so on. The scheme is simple and incurs minor overhead.

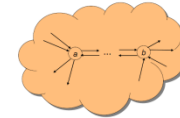


Fig. 1. An example scenario of information exchange.  $a$  and  $b$  are two wireless routers, each having packets to be routed to the other.

### I. INTRODUCTION

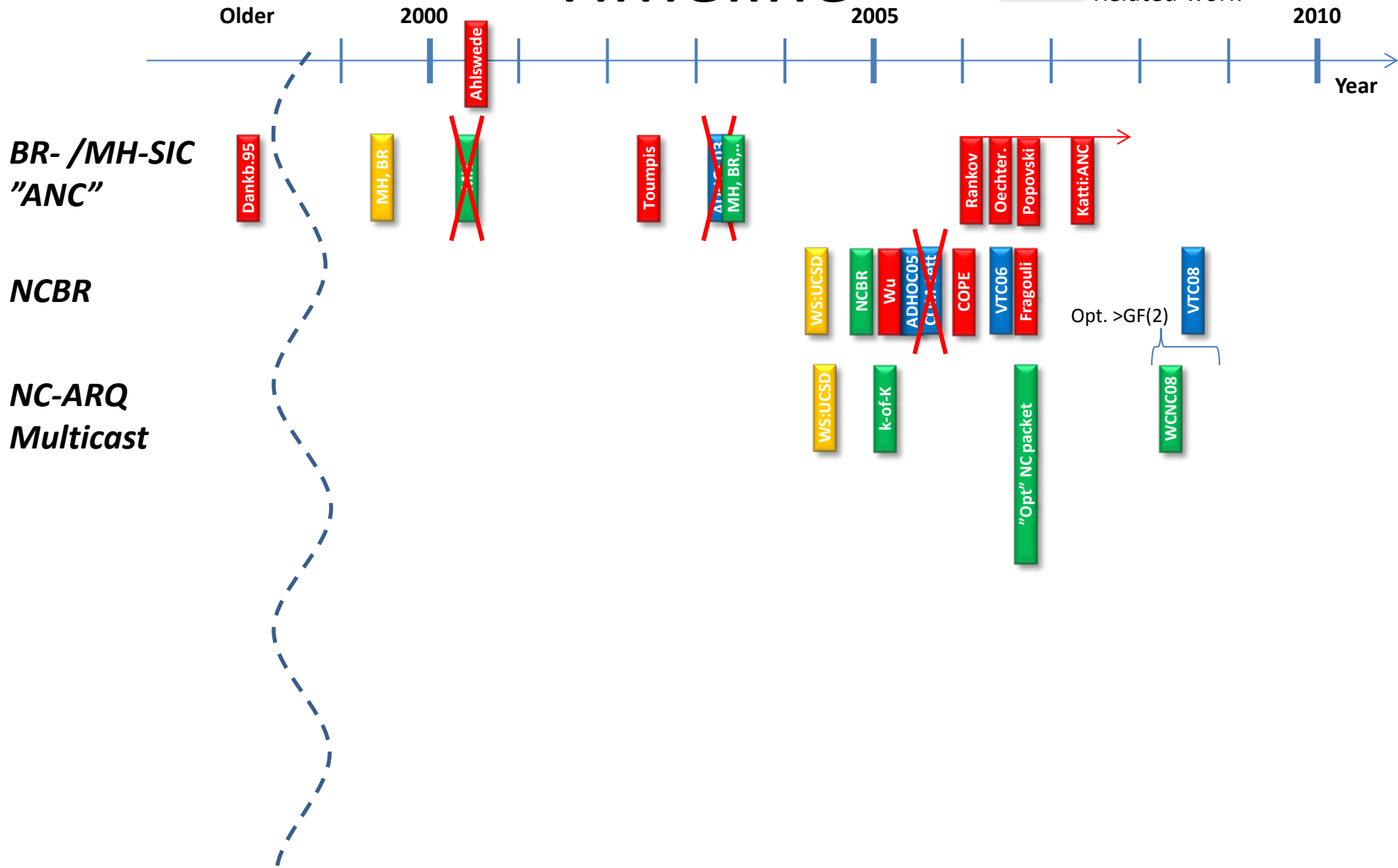
In this paper, we investigate the mutual exchange of independent information between two nodes in a wireless network. The processing of the two unicast sessions may outperform a

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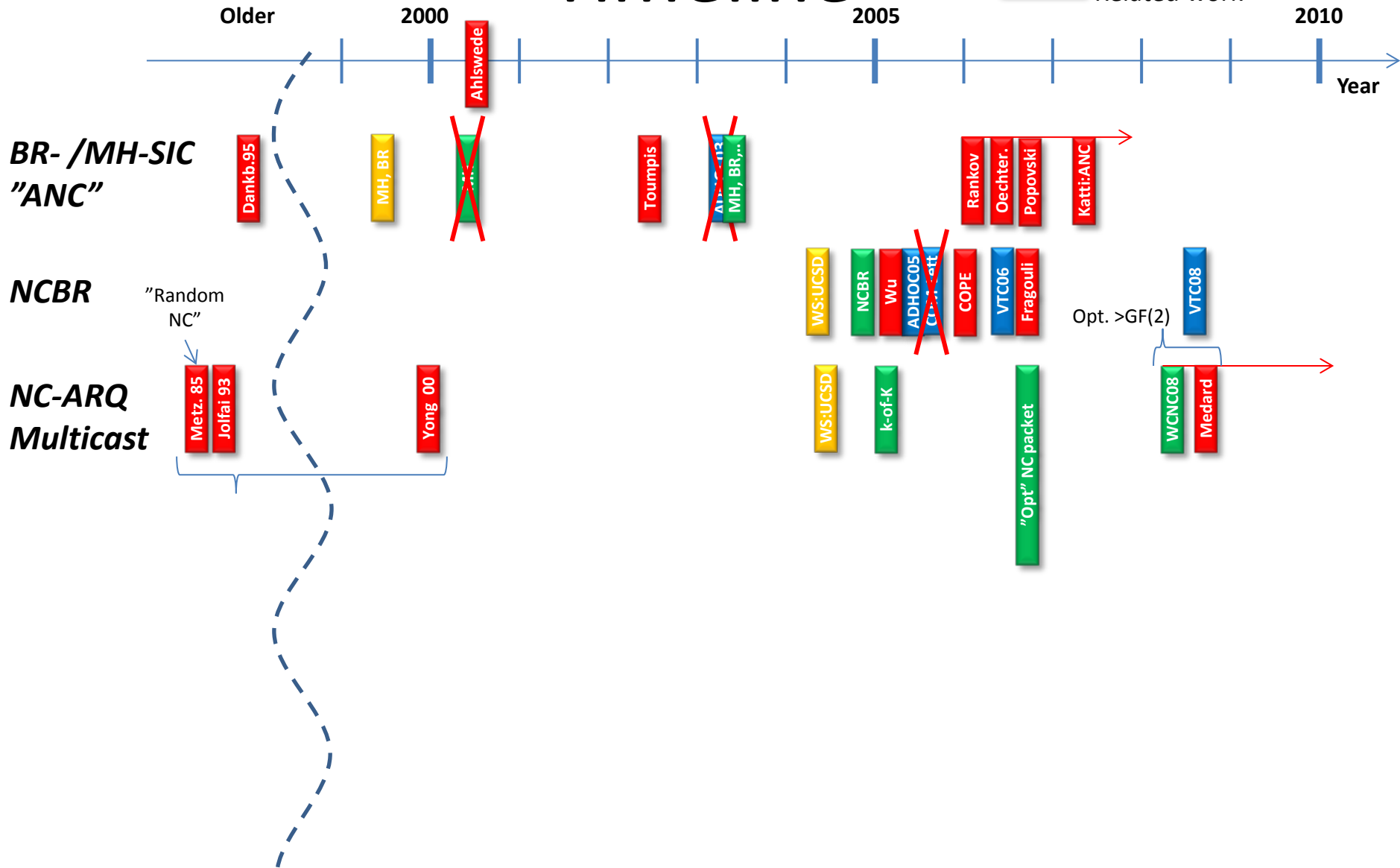
# Timeline

- Idea
- Patented
- Published
- Related work



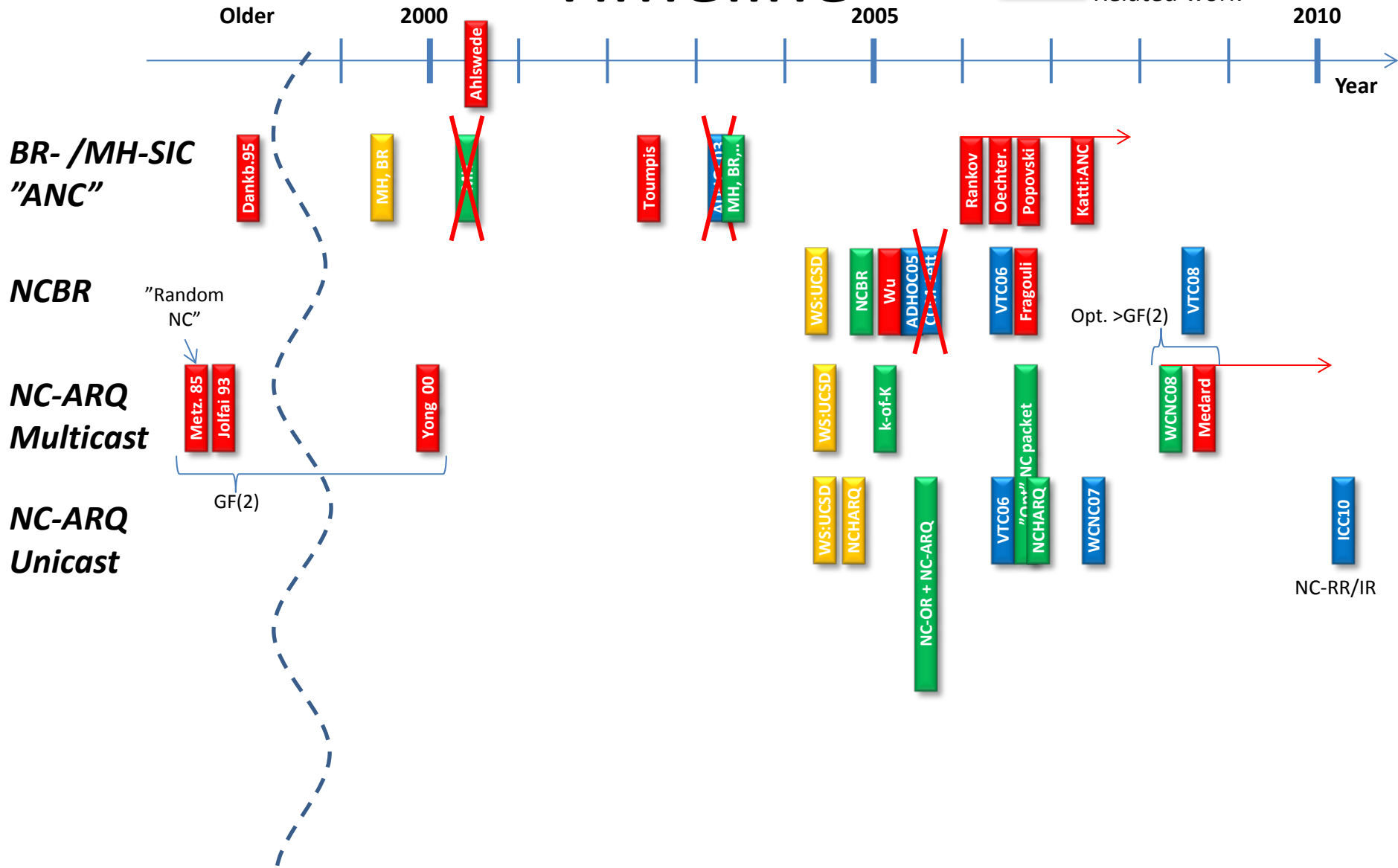
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- Idea
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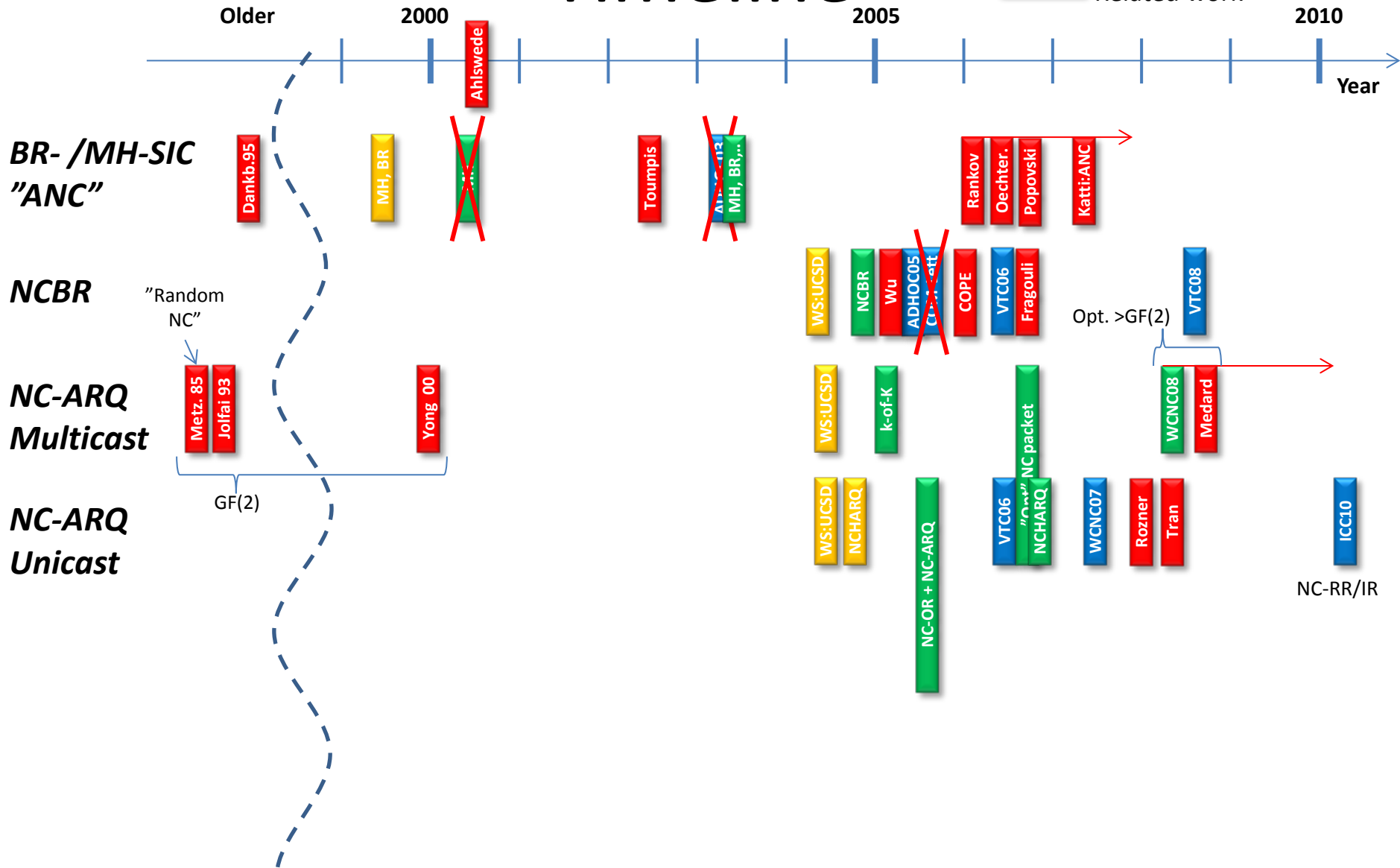
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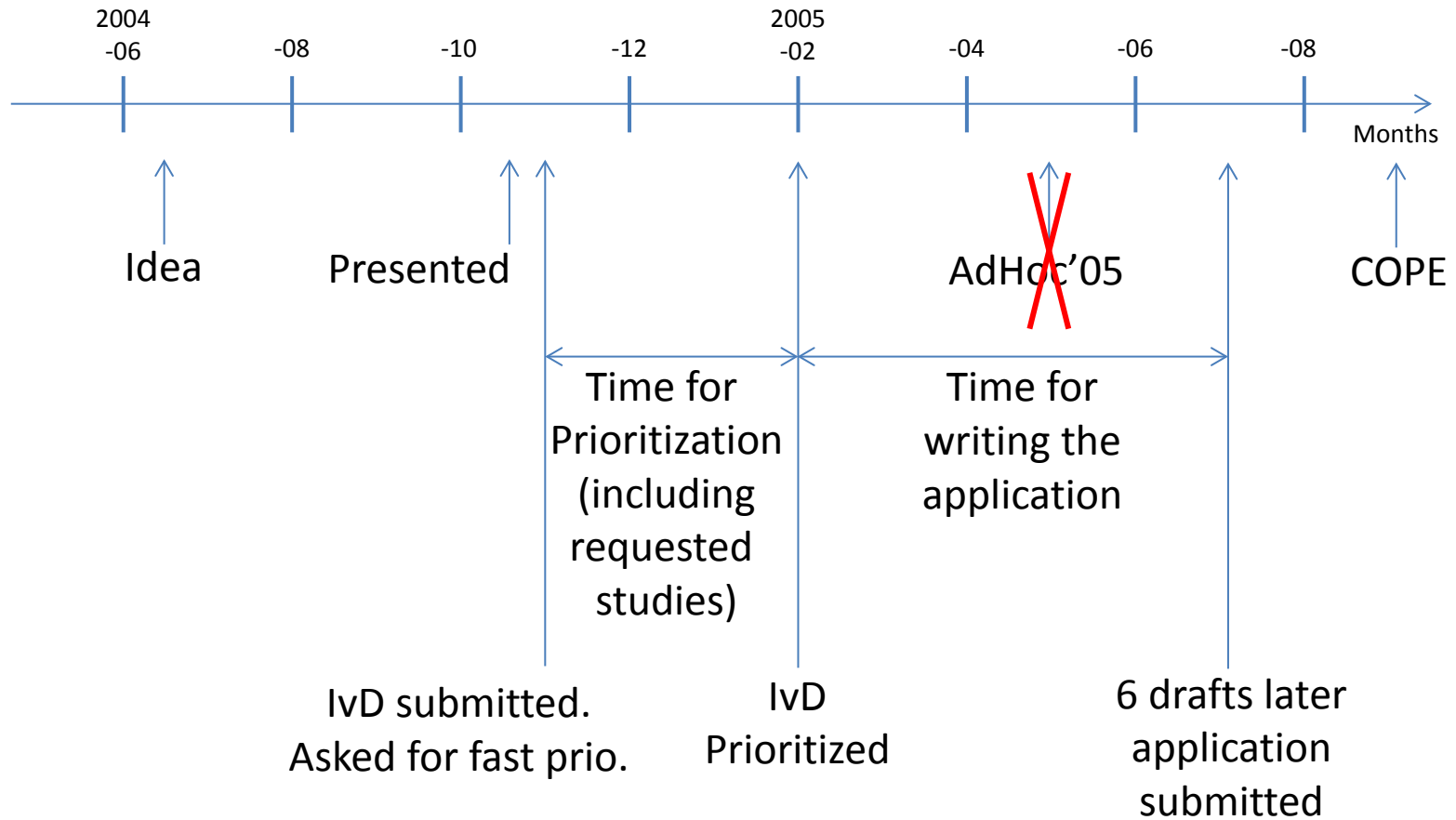
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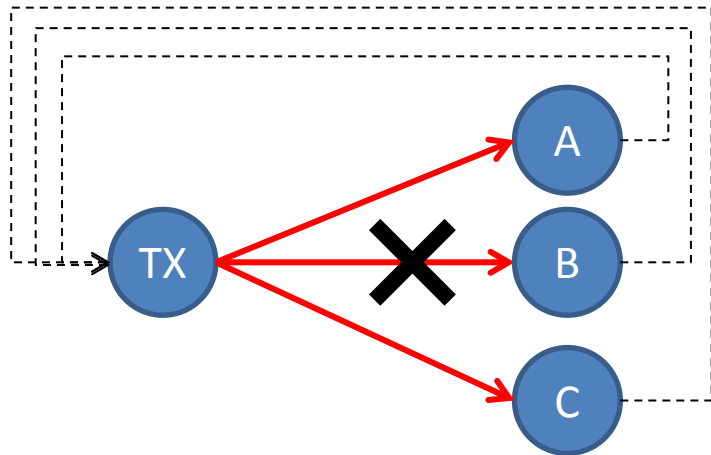


# NC-ARQ and NC-OR timeline

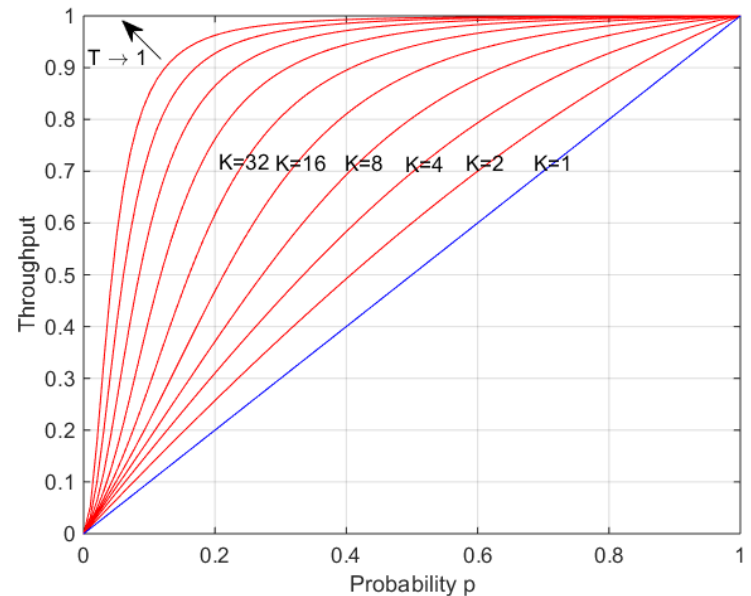


# NC-ARQ unicast

- From idea to publ: 2 years
  - Patentprocess delay
  - Challenging analysis
    - $K=2$  users – Easy!
    - $K>2$  users – Very tricky!

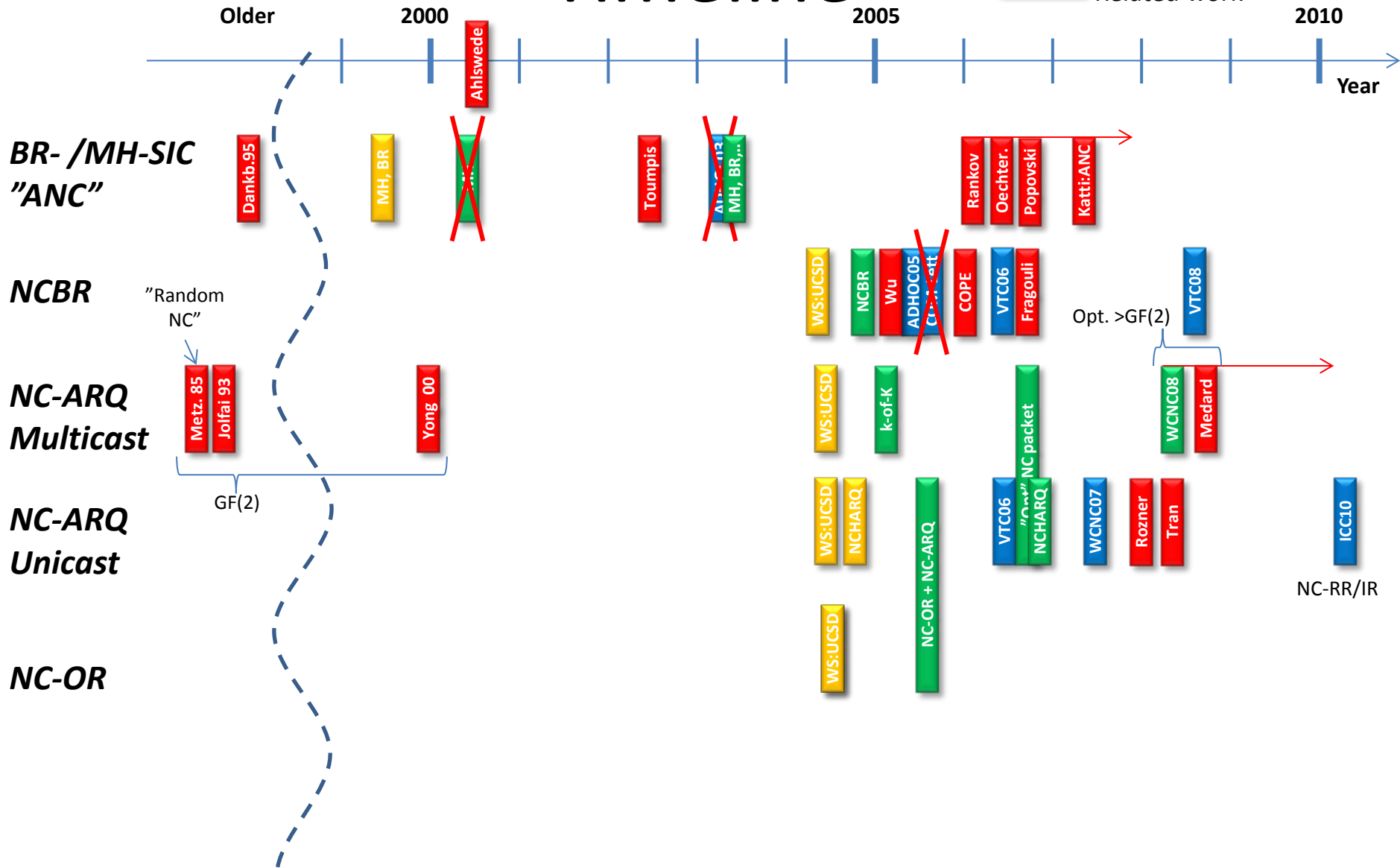


- For  $K>2$ , devised a suboptimal scheme for performance evaluation
  - Proved that  $T \rightarrow 1$  when  $K \rightarrow \infty$  and  $p \neq 0$



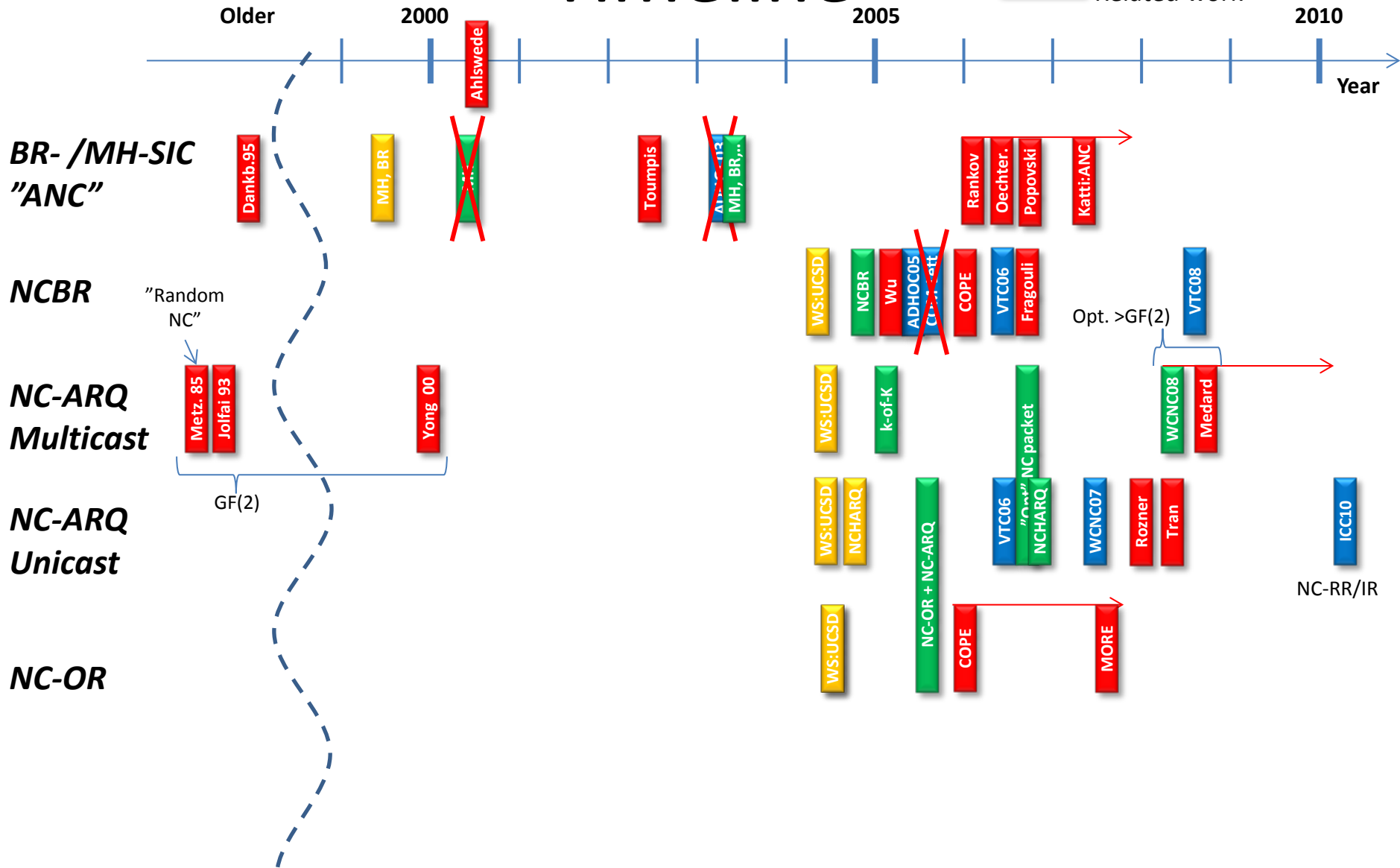
# Timeline

- Idea
- Patented
- Published
- Related work



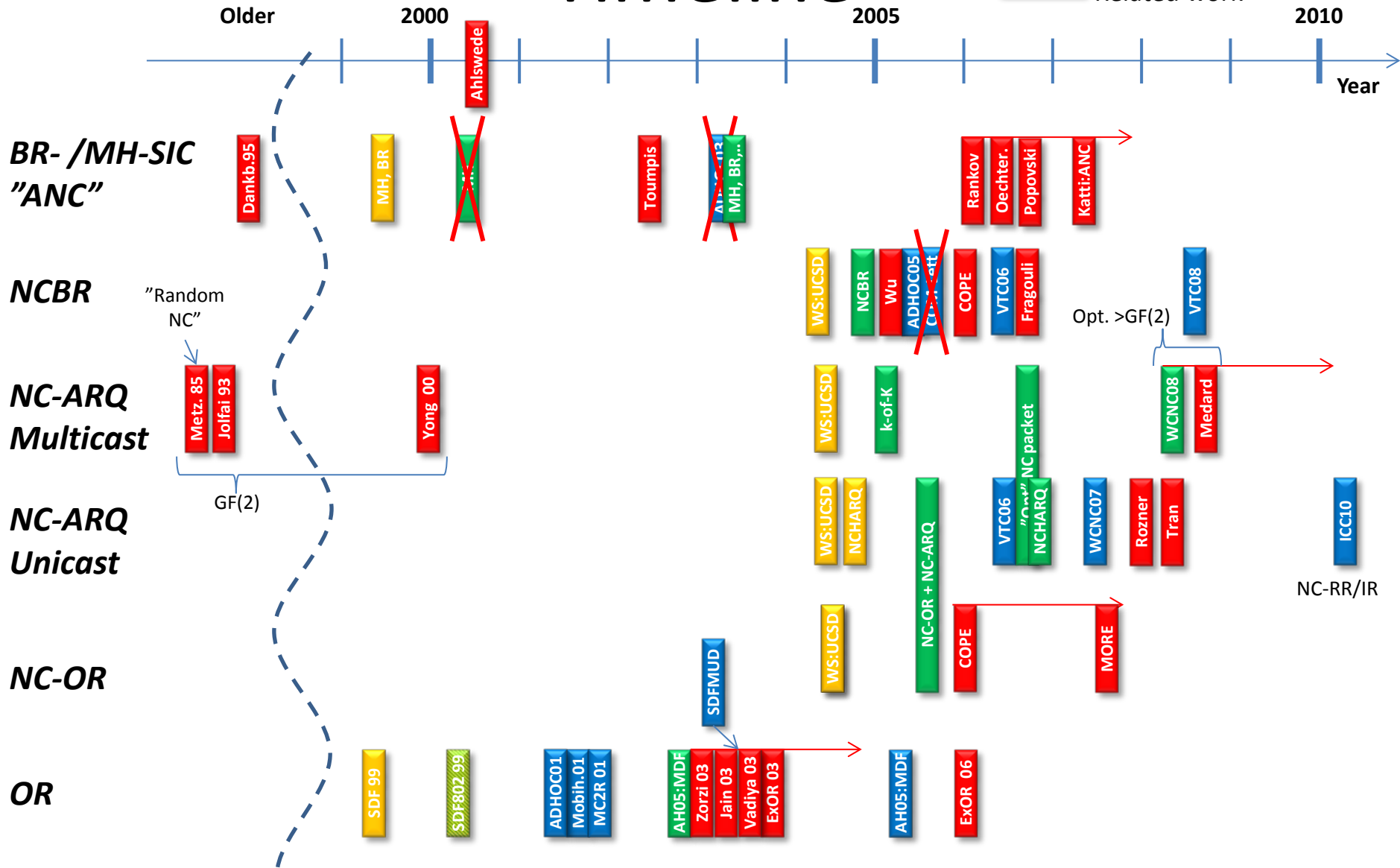
# Timeline

- Idea
- Patented
- Published
- Related work

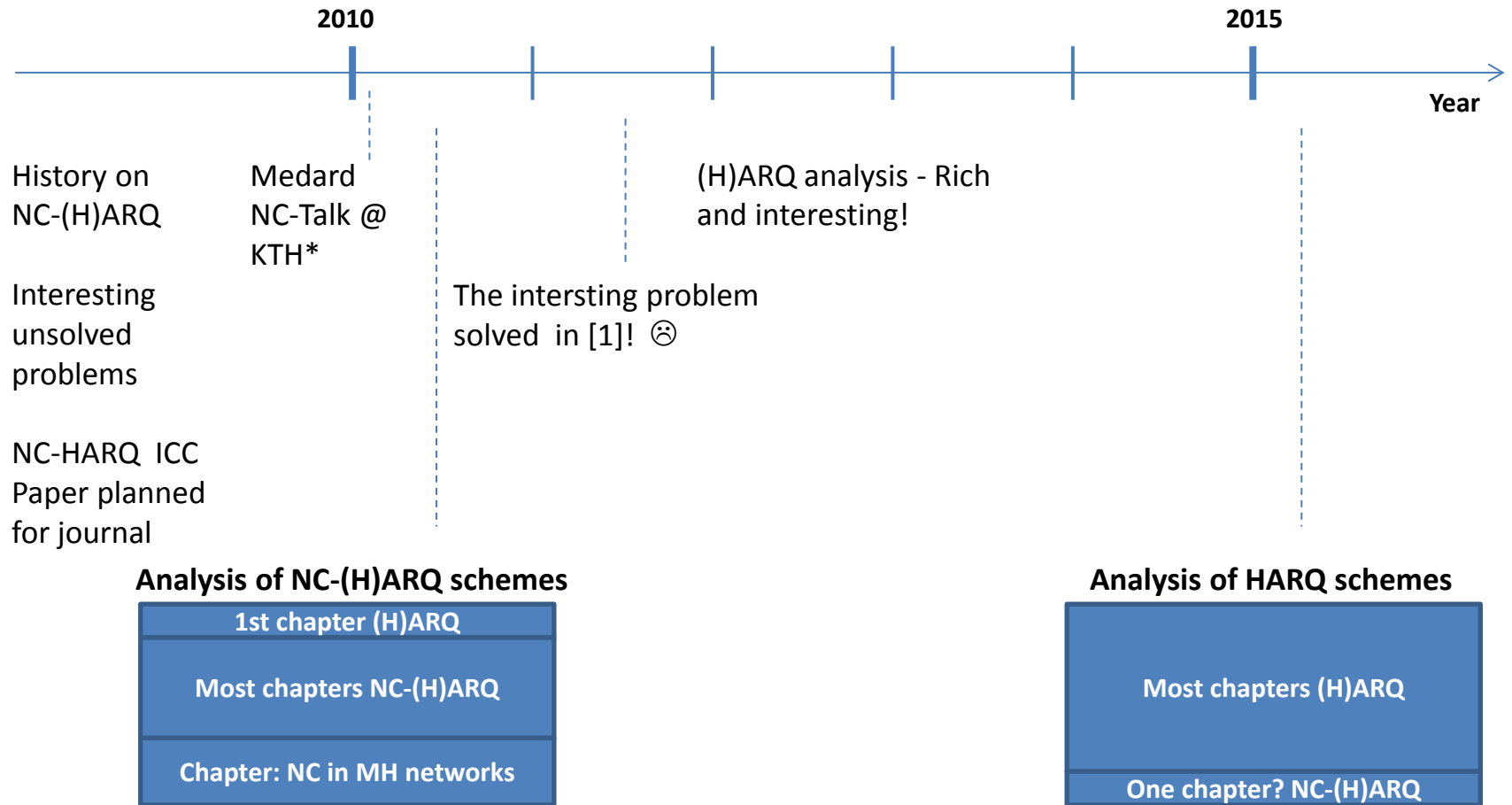


# Timeline

- Idea
- Patented
- Published
- Related work



# Why PhD research on (H)ARQ?



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# What did I learn?

- For early ideas
  - Get exposed to many areas, i.e. also outside telecom, and of theoretical and practical kind.
  - Strategically go to those WSs, and read those magazines, that deliver new early research ideas.
  - Set of relaxing/inspiring time for developing new ideas, principles, and avoid focus on deep analysis.
  - Think first, read up later
- For successful spread of work
  - Choose a catchy name
  - Publish many papers on the same idea
  - Go on tour
  - Be at a place where you have plenty of time
- Bad idea to patent for other!
  - Delays, or even hinder, a proper publication
  - No one read (or cite) patents
  - Unnecessary work
  - The gain = 0
- People don't always know, despite that they say they know, and many say they do.
  - Trust your instincts. If you believe in your idea, go for it.

The End

Questions?



# Related work

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