An Innovative SDR Architecture and MANET with Simultaneous Multiple Channel Reception

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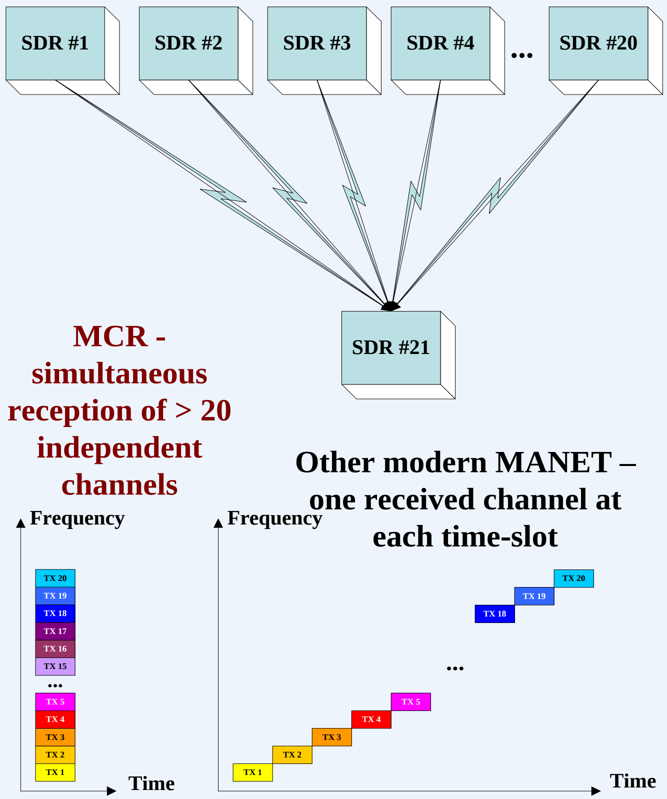

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Presentation Summary

- **Tactical MANETs usually employ 1(2) Hw receivers (per band), thus they are challenged by –**
  - ✓ **Tactical communication is mostly asymmetric, Rx rate >> Tx rates - <u>Receiver Bottleneck</u>**
  - ✓ **Besides "Intra-Unit" nets, "Inter-Unit" geographical Network Scalability is needed** (for SA, FA, CA)
  - ✓ **Units frequently Merge, pass-thru, Split -** need to avoid reconfiguration.

➔ ***Dynamic, High Scalability needed***

- **The Solution: Multiple-<u>Numerous</u>-Channel Reception architecture, based on Ultra WB ADC, Ultra Fast FPGA**
  - ✓ **<u>Hundreds</u> channels received (per band)**
  - ✓ **Almost unlimited Scalability, > 200 Mb/sec Rx rate!**

Scalability Challenge of 1–Channel TDMA Networks – Merging, Passing-thru and Splitting forces

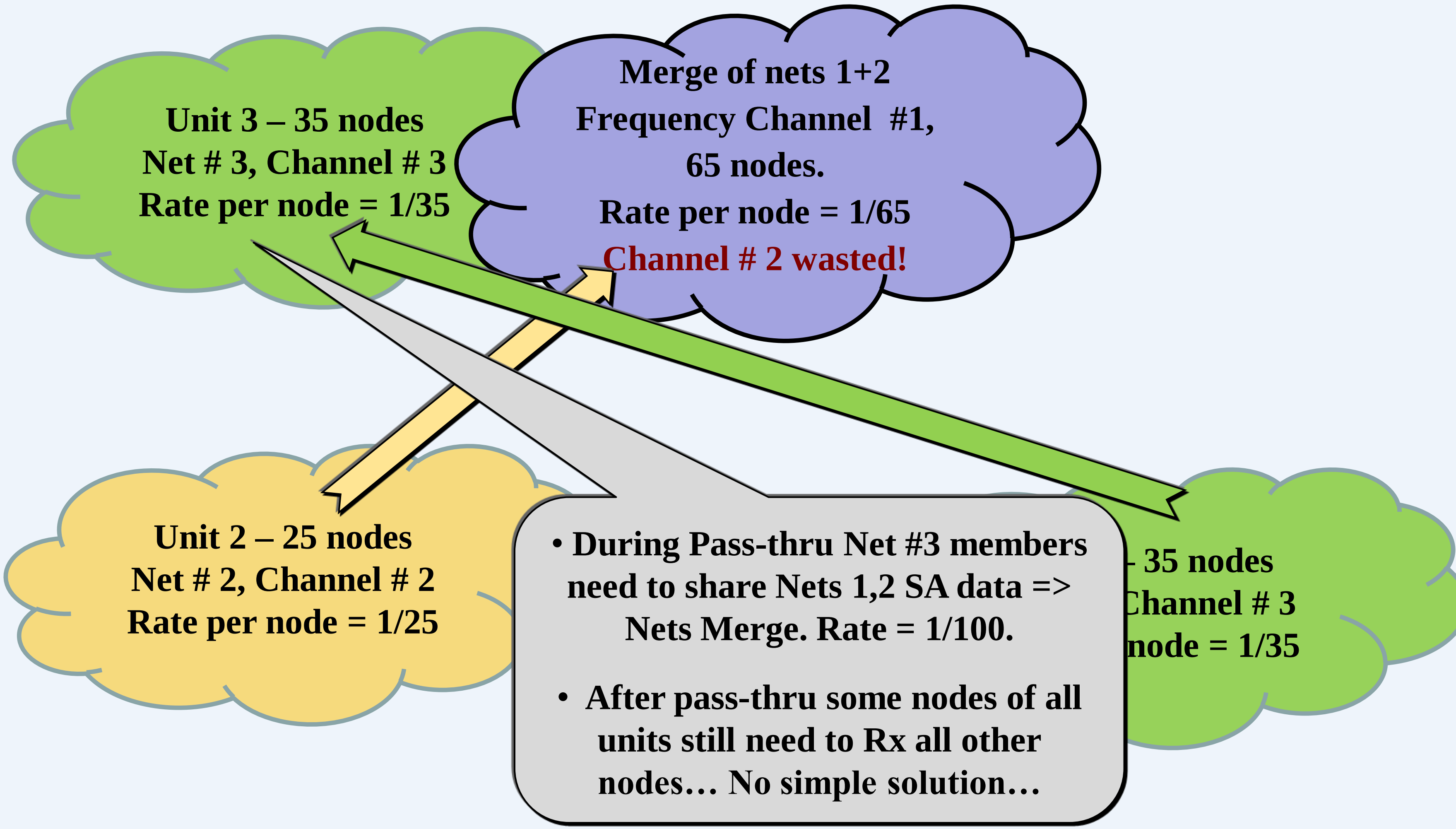
Unit 1 – 40 nodes
Net # 1, Channel # 1
Rate per node = 1/40

Initially, units are Isolated => Cross (Inter)-unit update rate can be low

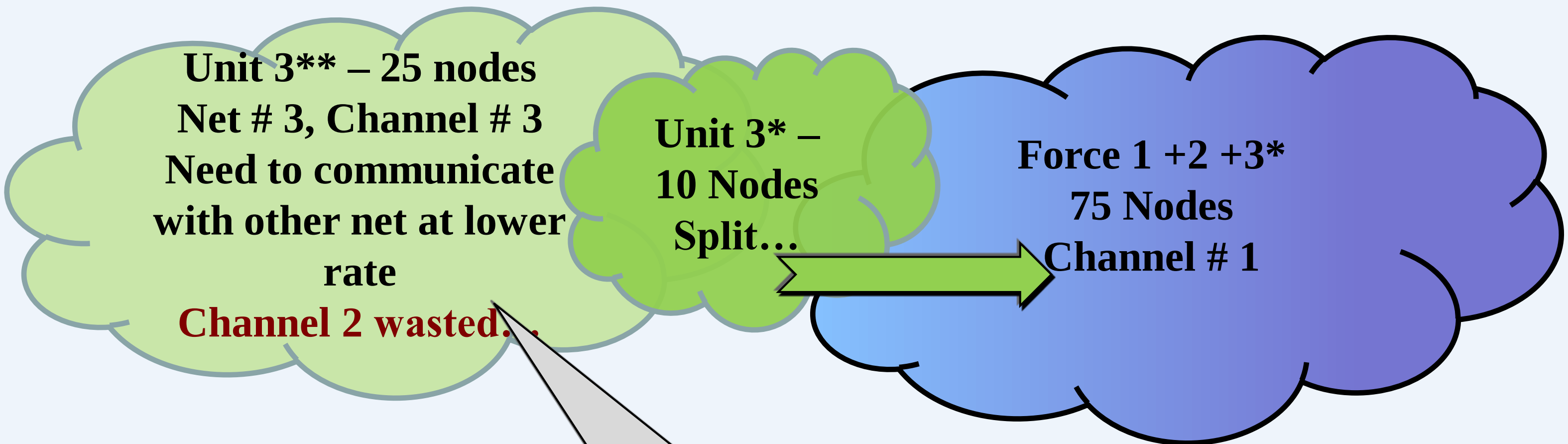
Unit 2 – 25 nodes
Net # 2, Channel # 2
Rate per node = 1/25

Unit 3 – 35 nodes
Net # 3, Channel # 3
Rate per node = 1/35

Scalability Challenge of 1–Channel TDMA Networks – Merging, Passing-thru and Splitting forces (2)



Scalability Challenge of 1–Channel TDMA Networks – Merging, Passing-thru and Splitting forces (3)



• After pass-thru, 10 nodes from U3 merge with 1+2. Some nodes of all units still need to Rx all other nodes… No simple solution…

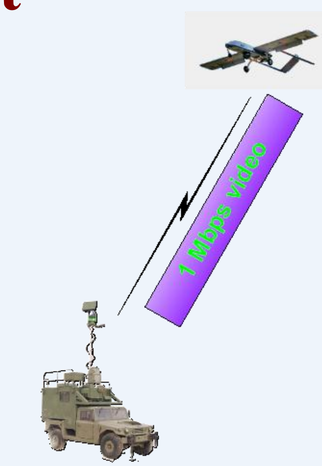
Scalability Challenge of 1–Channel TDMA Networks – Merging, Passing-thru and Splitting forces (4)

Unit 3** – 25 nodes

- ✓ **Allocation of channels to Intra-unit networks demands frequent reconfiguration in dynamical combat scenarios.**
- ✓ **"Merge/Split" algorithms – complicated, slow response, consume control bandwidth….**
- ✓ **SA/CA/FA Throughput of merged network don't scale - decreases linearly with N….**
- ✓ **Some available frequency channels can't be used….**

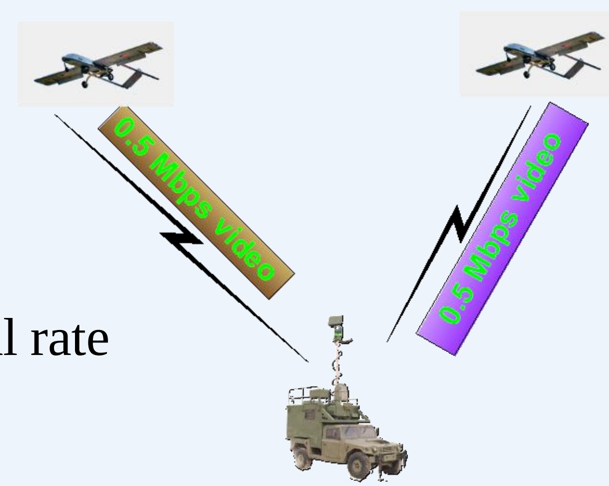
Simultaneous, Multiple Channel Reception solve all these problems!

Scalability Challenge of 1–Channel TDMA Networks: "Receiver Bottleneck" Effect



Total Rx rate 1 Mb/sec

Total Rx rate is still 1 Mb/sec..

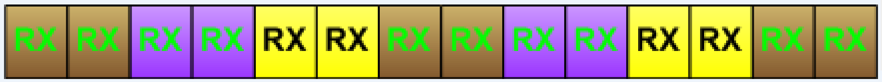


Reception of 2 Video Sources: Time Sharing.

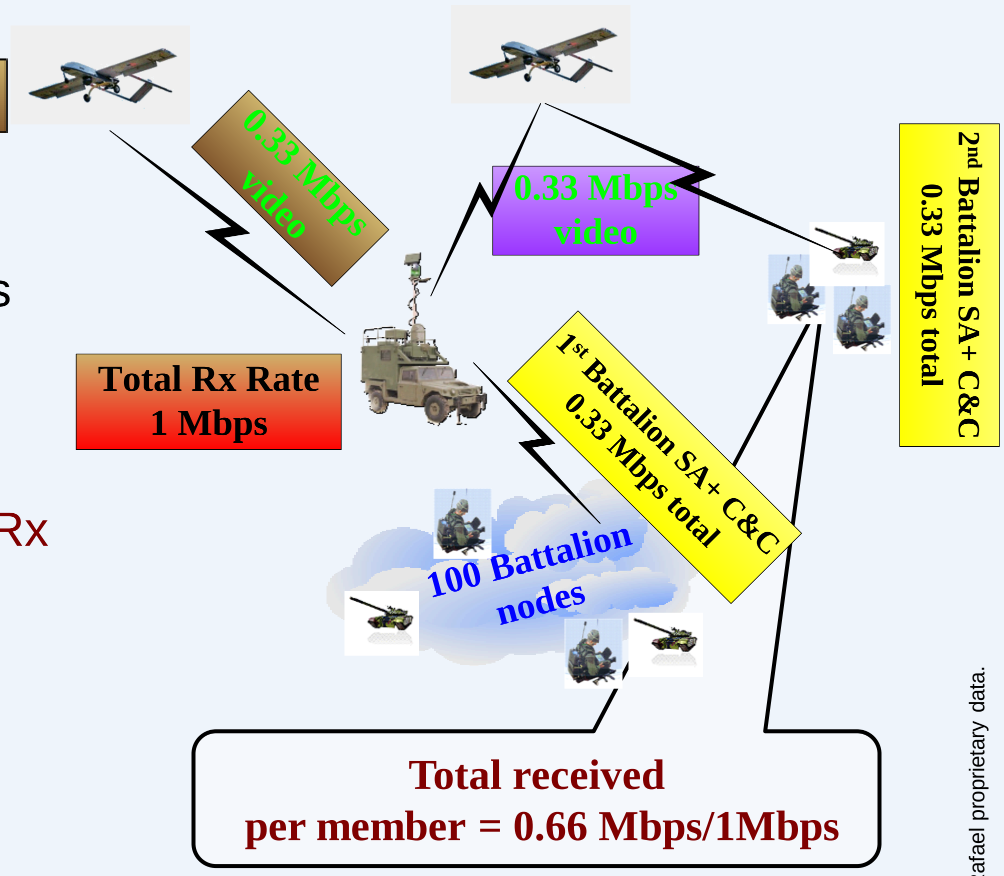
Tradeoff:

- Each source should be transmitted at 50% of total rate

Scalability Challenge of 1–Channel TDMA Networks: "Receiver Bottleneck" Effect (2)

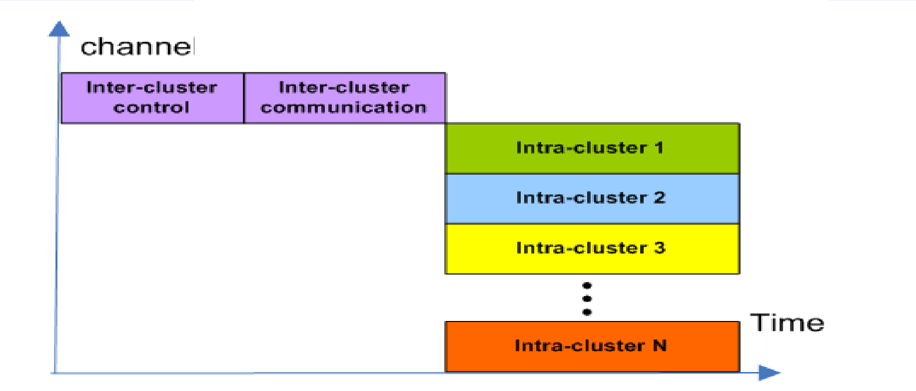


- 1st HQ Rx 2 Video Sources + 100 nodes Battalion SA + C&C messages
- 2nd Battalion need only 1 Video + Battalion SA + C&C – Could Rx 0.66 Mbps Video, but is limited by 1st HQ Rx bottleneck…
- **Even More Tradeoffs…**



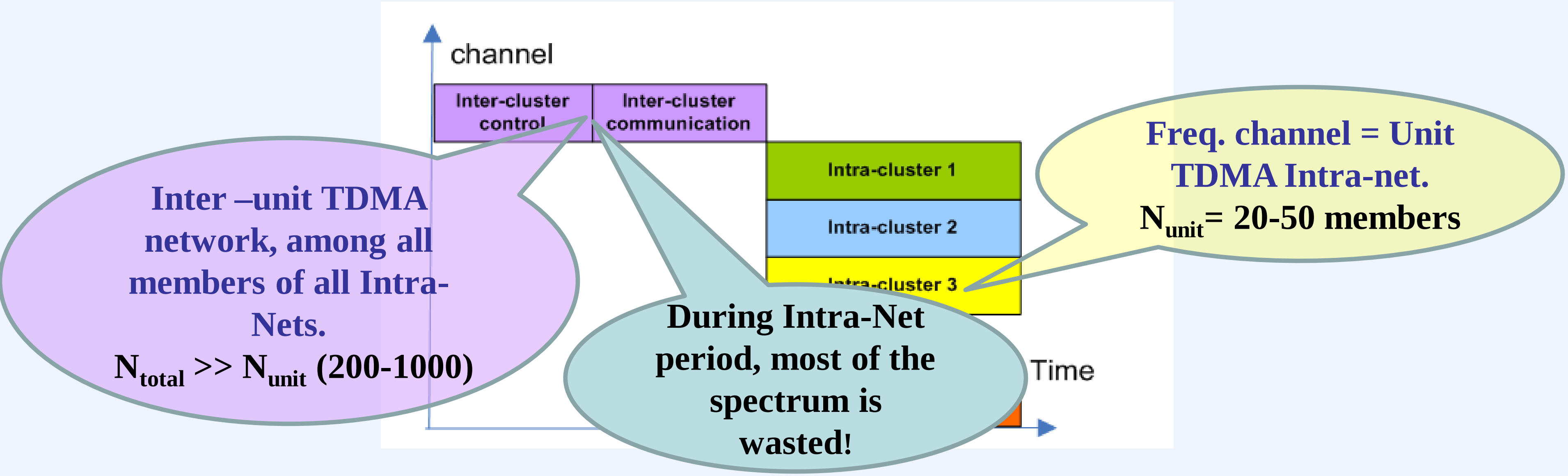
Throughput is bounded by the Bottlenecked Receiver, not by Tx...

A Common non-scalable approach - “Multiple 1-Channel TDMA” MANET



- ✓ **Most SDRs can receive only one channel per band at a time.** Once frequency has been set, the networking is done only among nodes tuned to that channel. The MAC is “blind” to all other channels.
- ✓ **A MANET system with a collection of channels, is in fact a collection of unconnected parallel MANETs,** with data rate limited by the BW of a single channel.
- ✓ **Time- Sharing between Intra/Inter- Unit Communication. Inter-Unit is done over a single channel.** ➔ **very low rate and waste of most of the spectrum during the Inter-Network time frame.**

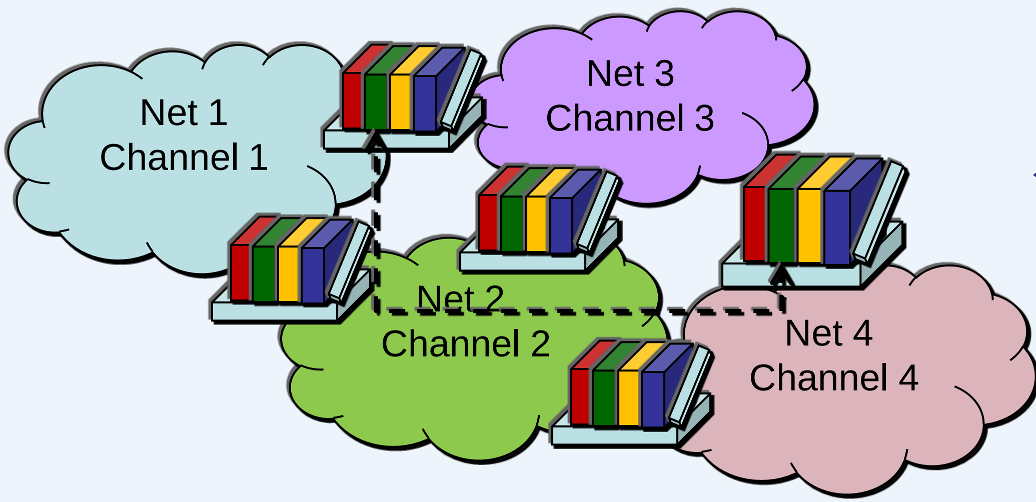
"Multiple 1–Channel TDMA" approach



- **Each radio can receive only a single channel (per band) simultaneously**
- **"Freq. Channel = <u>Intra-unit</u>** TDMA net" - A/C formation, Company, Battalion…
- **"<u>Inter-Unit</u>"** communication is done over a ***<u>Bottlenecked time shared single channel</u>***
  - ✓ Waste of spectrum!
  - ✓ **<u>Very low update rate</u> per each user in the Inter/ Cross-Unit network**
  - ✓ ➔ Inadequate SA/CA rates for merging units/formations.

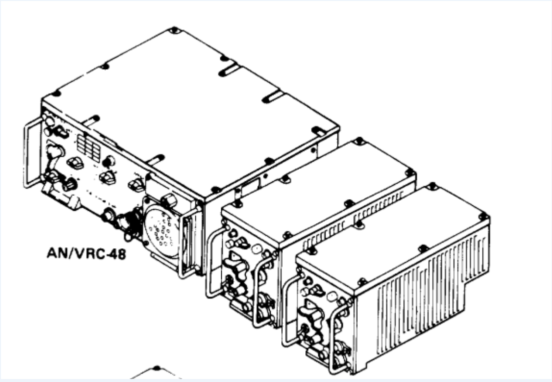
Another Low Scalability Approach – Multi Transceiver Inter-Net Gateways

- ✓ Each sub-net has several multi- transceiver SDRs which serve as gateways
- ✓ A(f1) => Gateway(f1) =>(thru Lan) Gateway(f2) => B(f2)



- ✓ Lots of expensive, heavy radios.
- ✓ If a Sub-net has L >4 neighbor Sub-nets, it needs L hardware transceivers…
- ✓ **Throughput still very low!** – every packet has to be retransmitted in all destination networks.

Historical Reminder….



VRC–44: The Commander's Radio (1965-1990+..)

- ✓ 1 Transceiver + 2 "Auxiliary receivers".
- ✓ Can Rx 3 unit or "functional" networks.
- ✓ Transceiver used for "Network Entrance".
- ✓ Command Vehicle/Post had 3-5 sets – Commander, Int., Fire, Logistics….

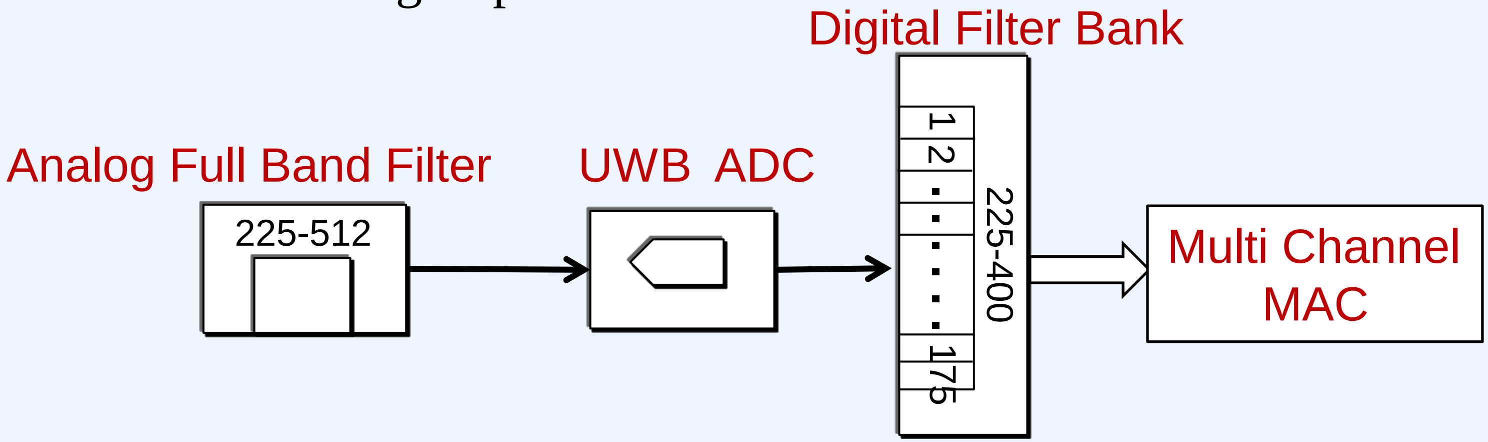
- **Ideally, A Military MANET SDR should have <u>numerous receivers</u> -** "Listen" to all desired Unit and Functional networks in it's neighborhood, Tx when it needs.

Multiple Channel Reception MANET SDR

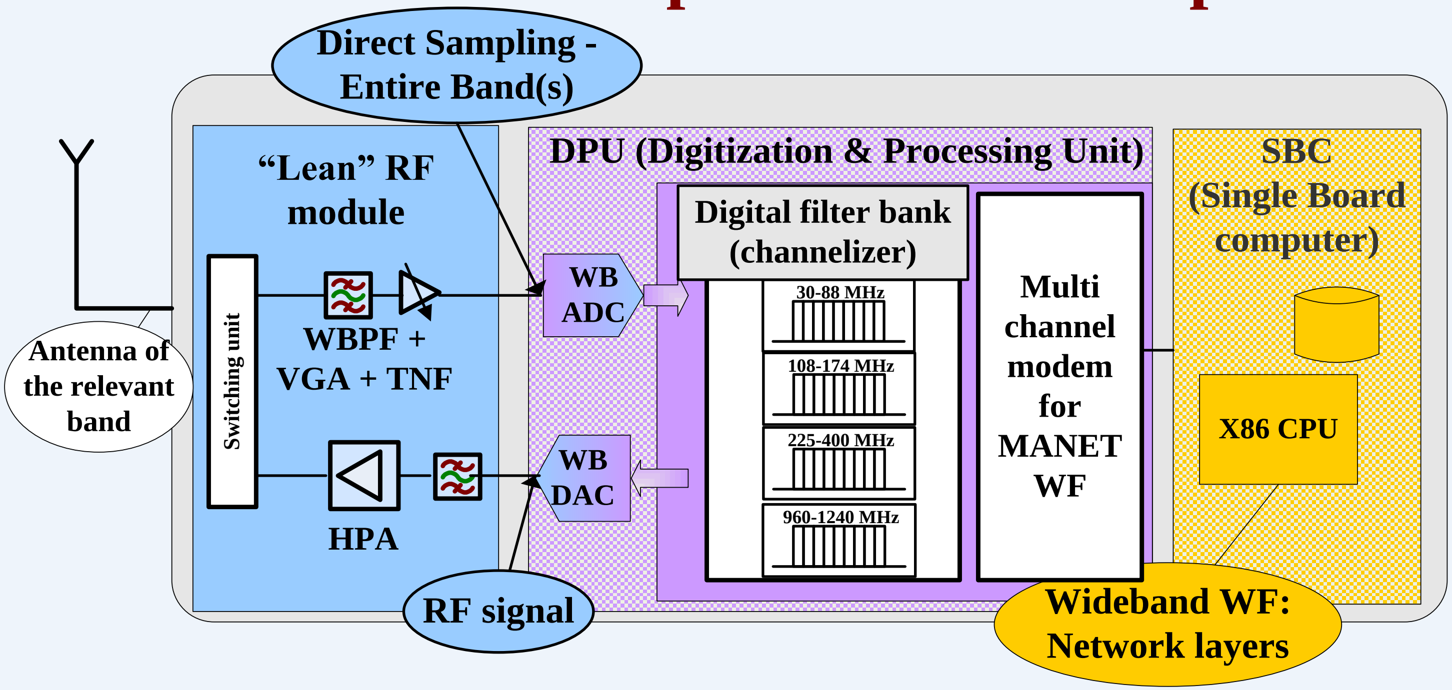
- **Preferably, A Military MANET SDR should have numerous receivers-** "Listen" to all desired Unit and Functional networks in it's neighborhood, Tx when it needs.
- **Multi-Channel digital Reception (MCR) architecture -**

✓ Direct sampling of a whole band(s) - Almost an "Ideal True SDR", **achieving 10÷100 fold increase in Rx throughput..**

✓ Tx frequency of a node is arbitrary in the allocated band, not related to unit or functional group.



Ultra Wide Band Multiple-Channel Reception SDR



- ✓ **Ultra Fast/ UWB ADC** – Dual 1.8 GSPS/12 bits or 1.2 GSPS/14 bits.
- ✓ **Ultra Fast FPGA** – more than 1 Tera-Ops/sec.
  - **Network ≠ Frequency channel.** Networks are ***logical.*** Channels allocated auto. by MAC.
  - **No reconfiguration during merge/pass thru – all nodes listen to all channels**
  - Tx node doesn't coordinate frequency with Rx nodes. Freq. Hoping – in Tx only...
  - **"Cognitive Ready"** – Rx is an instantaneous UWB Spectrum Analyzer…

Tactical MANET Periodical SA Messages (PM)

- **Basic service for C&C applications** (e.g., "Blue Force Tracking")
- **Periodical (refreshing) short messages – Multicast/Bcst packets for-**
  - ✓ **Situation Awareness (SA)** – Platform/Unit position/speed, status, tracked enemy targets– for COP and FA (Fratricide Avoidance).
  - ✓ **Collision Avoidance (CA)** – very high rate (10 Hz) needed in Airborne platforms; position and speed.
  - ✓ **Control packets** – rapid dissemination of network topology.
- **Destination – All nodes in <u>relevant geographical area</u>, regardless of unit association**
- **High Scalability needed while keeping high update rate**, in dynamic combat scenarios, Companies, Battalions, A/C formation – frequently merge or pass-thru.
- Need a scalable, fast and simple merging process w/o network reconfiguration.

PM-MCR MAC: providing a true scalable solution for broadcast PM data

- **The Ideal (static F/TDMA) Case -**
  - ✓ **N nodes** fully connected. **M frequency channels**. All nodes know IDs of all others.

CHANNELS

1	46	..	..	24	62	..	..	8	16	14
27	13	..	..	58	32	..	99	37	42	49
78	5	..	..	83	1	..	56	99	71	..
14	100	..	[illegible]	8	91	..	..	27	78	..
99	66	..	..	[illegible]	70	..	[illegible]	51	5	[illegible]

← N/M Time Slots → ← N/M Ti[illegible]

Nodes 1, 27, 78, 14, 99
Don't receive each other on 1st time slot. Random permutation of Tx schedule will enable receiving each other in following blocks.

  - ✓ **Half-Duplex Radio**, hence all radios Txing on same time-slot don't Rx each other . ⇨ a small rate loss of (M-1)/(N-1) – small for M<< N.
  - ✓ Tx order of every Block of N/M time–slots is a random permutation of the node IDs, with Seed = f(Block #).
  - ✓ Synchronized network, all nodes execute same permutations with identical seeds.

Static PM-MCR (F/TDMA) Performance

- **<u>The average Broadcast messages reception rate</u>** (every node Rx any other node) –

(1) $$R_{PM-MCR} = \frac{M}{NT_{slot}}\left[1-\frac{M-1}{N-1}\right] = M\left[1-\frac{M-1}{N-1}\right]R_{1Channel\,TDMA}$$

$$\xRightarrow[M \ll N]{} MR_{1Channel\,TDMA}$$

"Half-duplex Loss"

- **Average Throughput Gain of a <u>MCR SDR</u> w.r.t. 1-channel TDMA SDR, is ~ M = # of Channels….**
  - ✓ Compared to "M- Multiple/Stacked 1-TDMA" Inter-net, where X<1 of the time-frame is allocated to the Inter-units network, ATG is 1/(1-X) higher than (1).
  - ✓ **Example: N = 501** nodes, **M= 21** Channels, **X= 0.5** of time frame for Inter-Unit net => **ATG** of the Inter-Unit communication w.r.t. "M-stacked 1-TDMA" = **40.3**

Static PM-MCR (F/TDMA) - continued

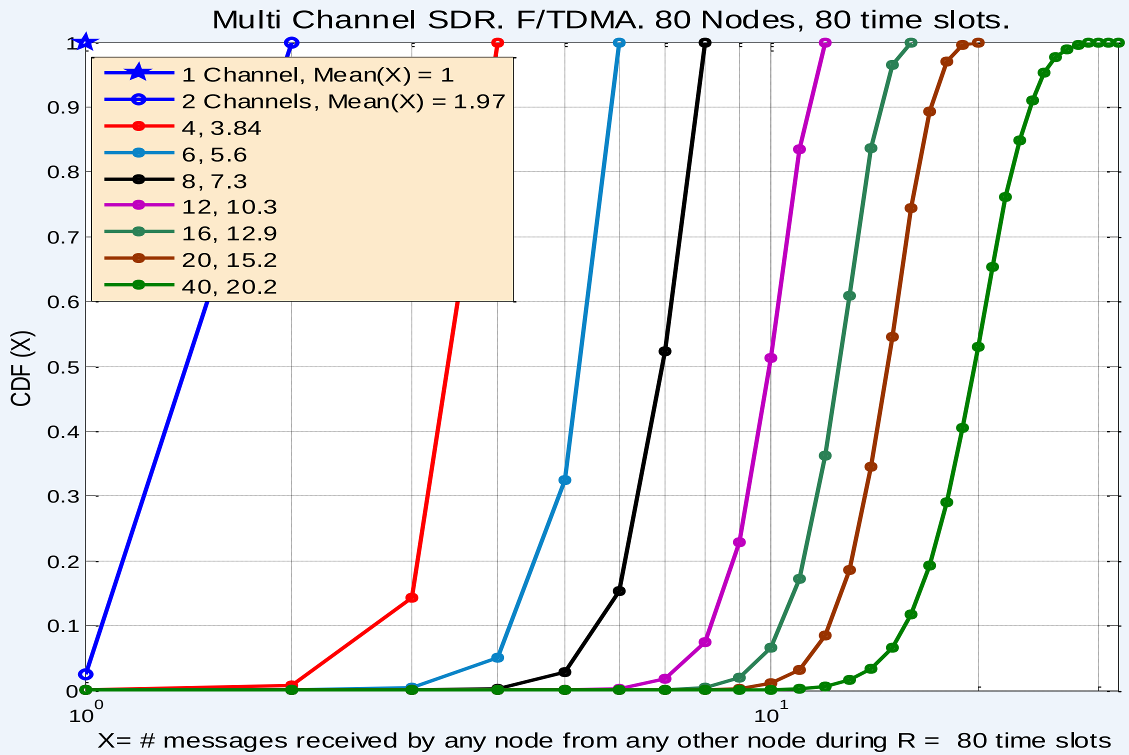
- Due to random permutations of node's k "transmission cell" within a block of {M frequency channels X (M/N) time-slots}, and the random # times node's k transmissions are not heard by some other nodes transmitting at the same time slot with k, the probability of reception is Binomial –

(2)
$$Prx_{ijL}(k) \triangleq Prob\{Node\ i\ received\ node\ j, k\ times\ during\ \ R\ time-slots\}$$
$$= \binom{L}{k} Prx_1{}^{k}(1-Prx_1)^{L-k};\quad k=0,1,2,..L;\quad L=\frac{RM}{N}$$

(3)
$$Prx_1 = 1 - \frac{M-1}{N-1}$$

- The CDF however rises sharply => "Fairness".
- Simulations show that the theoretical CDF is achieved within 2-3 frames of (N/M) Time-slots.

Static PM-MCR (F/TDMA) - continued



- **Discussion:** For **80 Nodes, 200 Time-slots/sec**, if **4 channels** are allocated for PM service, **Average reception rate** =2.5*3.8**= 9.6 Messages/sec**, compared to **2.5 Mess/sec with a 1-Channel TDMA.**
- More than 2.5*2=5 Mess/sec are received with 100% probability.
- Only 10% are received at rate lower than 8.5. Mess/sec

PM-MCR almost achieves Shannon's bound for 1-Channel UWB TDMA (Full Mesh case)

- **Objective:** Show optimality of MCR F/TDMA – it almost achieves Shannon's Bound for a 1- channel UWB TDMA, with the same BW of M- Channels MCR.
- **However, practically MCR F/TDMA MANET is always better than a 1-channel UWB TDMA, since UWB requires –**
  - ✓ Very high peak power ($P_{uwb} = M*P_1$)
  - ✓ A wide contiguous spectrum allocation ($B_{uwb} = M*B_1$)
  - ✓ Packet length $T_{UWB} = T_1/M$ is too short for allowing Guard Time for long range, airborne communication.
  - (e.g.: 100 Km range ⇔ 0.33 Millisec GT. Packet size = 1 Kbyte ⇔ 1 Millisec at 1 Mb/sec, 0.025 Millisec at 40 Mb/sec << 0.33…...)
- **Proof Outline –**
  - ✓ Requiring Average Tx power is equal for both cases ⇔ Equal Range
  - ✓ Requiring # of bits/packets (neglecting Guard Time) is equal in both cases

PM-MCR almost achieves Shannon's bound for 1-Channel UWB TDMA

Definitions:

N- # Nodes. **M**- # channels. **B_u** = **$M*B_1$** - BW of UWB radio. **T_1,T_u**– Time slot length. **P**- peak

Multi Channel SDR | **UWB 1-Channel SDR**

(4) **Shannon's Bound**

$$C_1 = B_1 Log(1 + SNR_1)$$ per channel.

$$C_{uwb} = MB_1 Log\left(1 + \frac{P_u}{MP_1} SNR_1\right) = MC_1$$

Requiring Average Tx power is equal for both => $P_{uwb} = M*P_1$

(This condition also implies identical SNR, thus identical reception range)

(5) Node's Message Rx Rate, from eq. (1) -

$$R_{PM-MCR} = \frac{M}{NT_1}\left[1 - \frac{M-1}{N-1}\right]$$

$$R_{uwb} = 1/(NT_u)$$

Requiring # of bits/packets, C*TS *(neglecting Guard Time)*, **is equal in both cases:**

(6)

$$\frac{T_1}{T_u} = \frac{C_{uwb}}{C_1} = M$$

PM-MC almost achieves Shannon's bound for 1-Channel UWB TDMA (2)

Substituting (6), (5) into (4), the message rate ratio is –

$$\frac{R_{PM-MC}}{R_{UWB}} = \frac{MNT_u}{NT_1}\left[1 - \frac{M-1}{N-1}\right] = \left[1 - \frac{M-1}{N-1}\right] \xrightarrow[M \ll N]{} 1$$

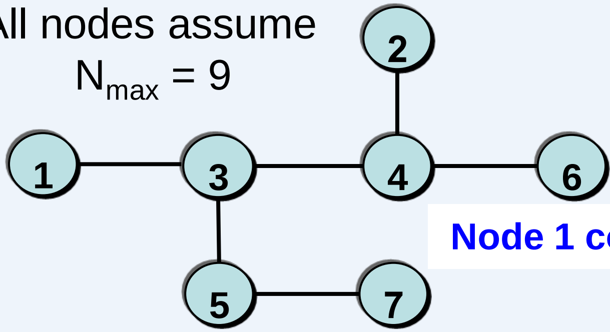
- ✓ **This theoretical result shows that PM-MCR (for static, fully connected mesh case) almost achieves Shannon's bound.**
- ✓ **However, practically MCR MANET is always better than a 1-channel UWB TDMA, since UWB requires –**
  - ✓ Very high peak power ($P_{uwb} = M*P_1$)
  - ✓ A wide contiguous spectrum allocation ($B_{uwb} = M*B_1$)
  - ✓ Packet length $T_u = T_1/M$ is too short for allowing Guard Time for long range, airborne communication.
    (e.g.: 100 Km range ⇔ 0.33 Millisec. Packet size = 1 Kbyte ⇔ 1 Millisec at 1 Mb/sec, 0.025 Millisec at 40 Mb/sec << 0.33…...)

PM-Multiple Channels Adaptive distributed F/TDMA MAC

- **Previous example was for static mesh-** not adequate for high mobility, nodes are not aware of all other active nodes in the whole Inter-network.
- **Adaptive PM MAC for MCR** – A 2 Dimensional generalization of a common class of "Adaptive TDMA" algorithms (e.g. MALS, SEEDEX, NAMA alike –[1-4]), where -
  - ✓ There is a "Network joining" (and leaving) process, during which a new node learn about its 2-3 hops "Contention Neighborhood" (all nodes that could contend with it directly or interfere with its destinations as "Hidden Terminals").
  - ✓ For each Time/Frequency cell (TFC) a distributed election algorithm is used to select one transmitter, according to a deterministic "Priority function", which induces a deterministic order among all contending nodes in a neighborhood, by means of deterministic function (e.g. a permutation of {Nodes ID Vector}, PRNG, Latin Square..). This function is based on a "seed" = f(TFC) known to all contenders.
  - ✓ This election ensures that all nodes in the one-hop neighborhood of the transmitter will receive data without any collision. The seed pseudo-randomly changes in each TFC, thus ensuring (some) fairness among nodes.

Example of an Adaptive distributed TDMA Algorithm

All nodes assume $N_{max} = 9$



Node 1 contenders: {3,4,5}

Scheduling matrix – PRN permutations of {1,2,…9}

TS 1	6	3	7	8	5	1	2	4	9
TS 2	7	2	8	5	6	9	4	1	3
TS 3	4	3	7	9	8	1	5	6	2
TS 4	5	7	8	3	6	1	2	4	9
TS 5	4	9	2	6	5	1	7	8	3
TS 6	9	6	2	1	3	8	7	4	5
TS 7	1	7	8	4	2	9	5	6	3
TS 8	5	3	9	7	4	1	8	2	6
TS 9	3	2	6	4	9	8	7	1	5
TS 10	9	2	1	6	8	3	7	4	5

			Time Slots									
# Tx in 10 TSlots	Node	Contenders	1	2	3	4	5	6	7	8	9	10
3	1	3,4,5	3	5	4	5	4	1	1	5	3	1
2	2	3,4,6	6	2	4	3	4	6	4	3	3	2
1	3	1,2,4,5,6,7	6	7	4	5	4	6	1	5	3	2
2	4	1,2,3,5,6	6	2	4	5	4	6	1	5	3	2
2	5	1,3,4,7	3	7	4	5	4	1	1	5	3	1
2	6	2,3,4	6	2	4	3	4	6	4	3	3	2
2	7	3,5	3	7	3	5	5	3	7	5	3	3
		Tx Winner	6	2	4	5	4	1	1	5	3	1
				7				6	7			2

Fairness depends on –

- Type of “Order Inducing Function”
- N_{max}
- “Fairness window length”

Optimizations possible…

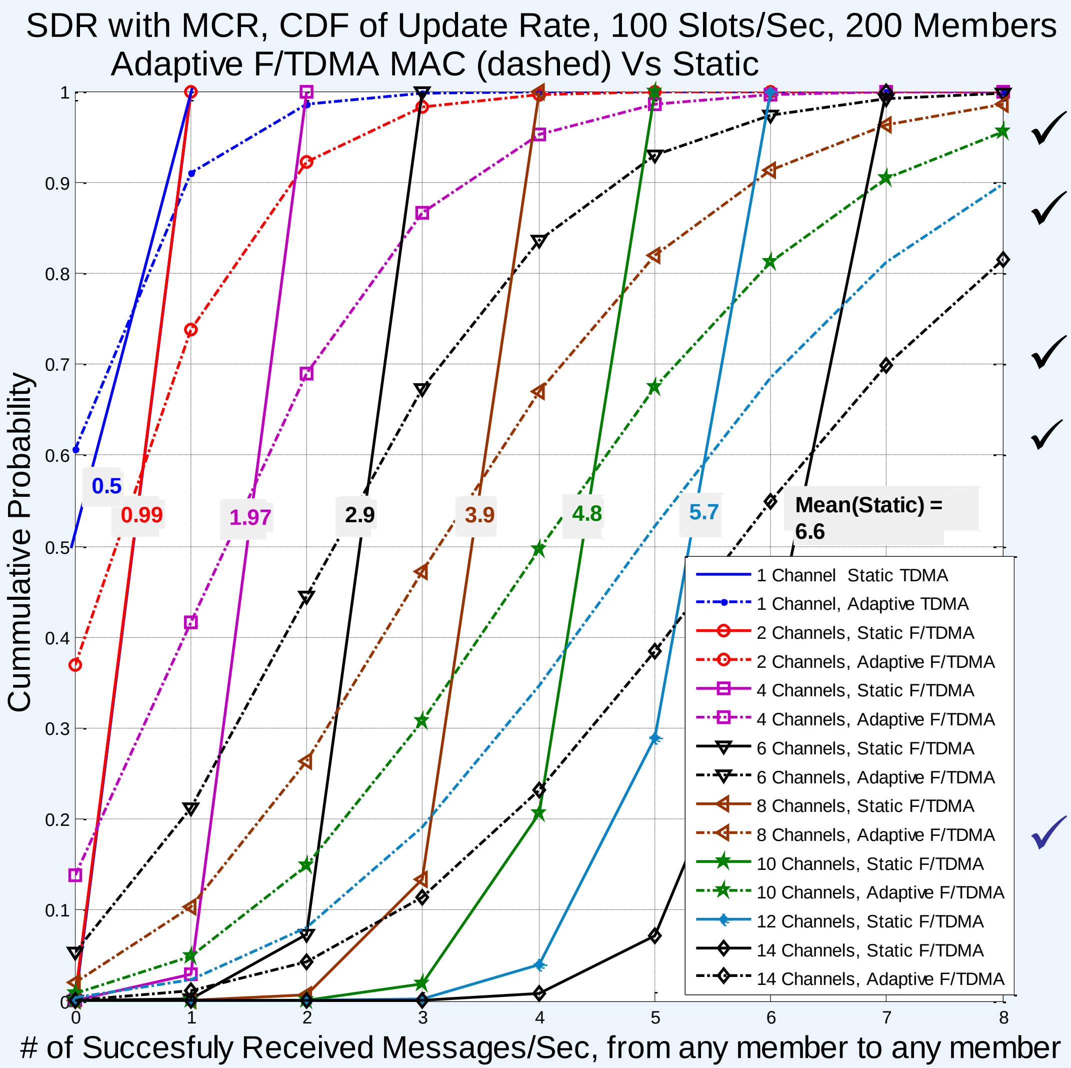
e.g., LS is better, but more computationally demanding for large N_{max}

Notice that algorithm achieves some Spatial Reuse

PM-Multiple Channels Adaptive F/TDMA MAC

- **Extension to Multi Channel SDR:**
  - ✓ The 1-channel Adaptive TDMA algorithm is run per each Time/Frequency Cell (TFC) with a PR seed = f(TFC), known to all nodes. The node with the highest priority among it's known contenders elect itself to transmit.
  - ✓ If a node wins 2 TFCs in a Time-Slot, it transmits in only one of them (*).
- **Optimization allows QOS and better fairness –**
  - ✓ Type of "Order Inducing Function" (Latin Square, PRN, Hash…)
  - ✓ Total # IDs (Nmax) w.r.t. actual network size.
  - ✓ When a node needs higher throughput – it is given several IDs.

“Neighborhood aware” PM-MCR Adaptive F/TDMA MAC

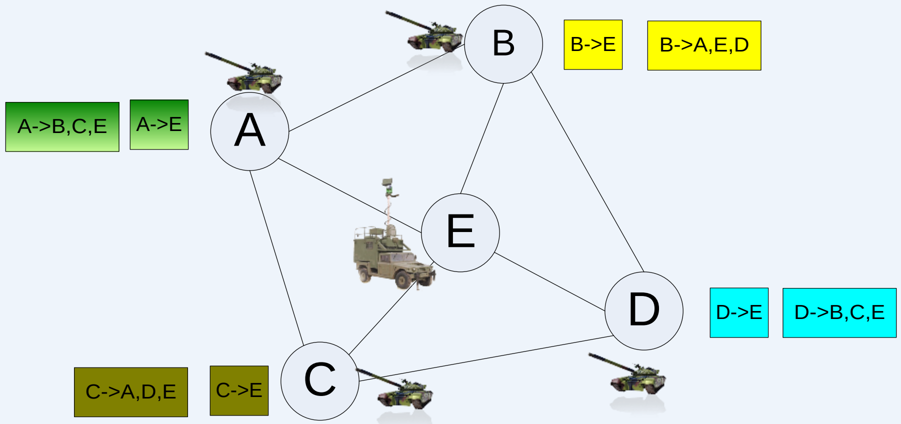


- ✓ Full lines – Static MAC
- ✓ Dashed lines – simulation of adaptive F/TDMA
- ✓ All nodes are fully connected
- ✓ **# Channels to ensure 3 Mess/Sec:**
  - **“6.2” Mean** (Eq. 1, roughly M times vs. 1 -Channel SDR)
  - **8 Ch. at 50%**
  - **10 Ch. at 70%**
  - **12 Ch. at 80%**
- ✓ **“Full Mesh” is worst case** – in other scenarios Throughput & Fairness are better due to Spatial Reuse

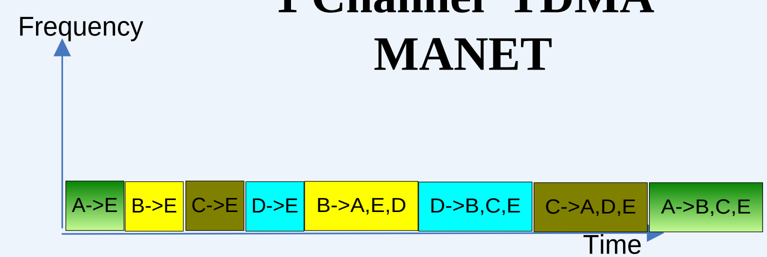
Full- Mesh is worst case Topology (better spatial-reuse in other scenarios)

Network Delay- arbitrary length Unicasts /Multicasts

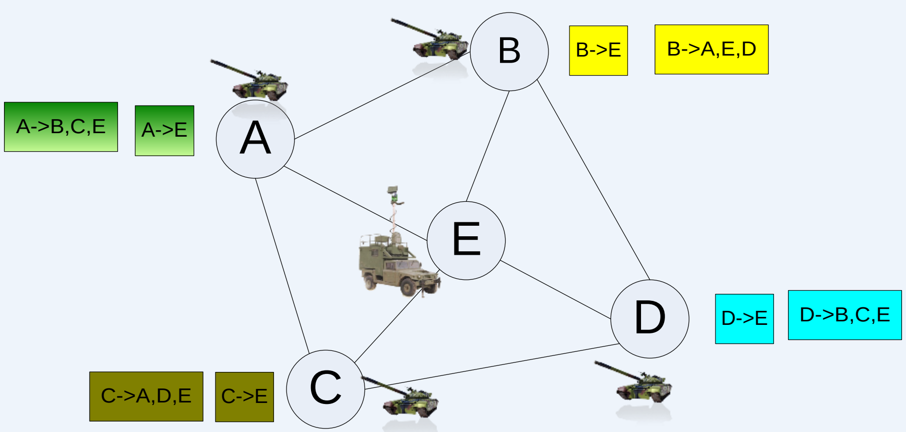
The bottleneck of 1 Channel Manets is the receiver….

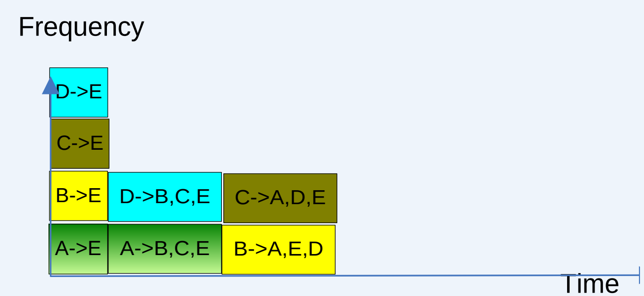


1 Channel TDMA MANET

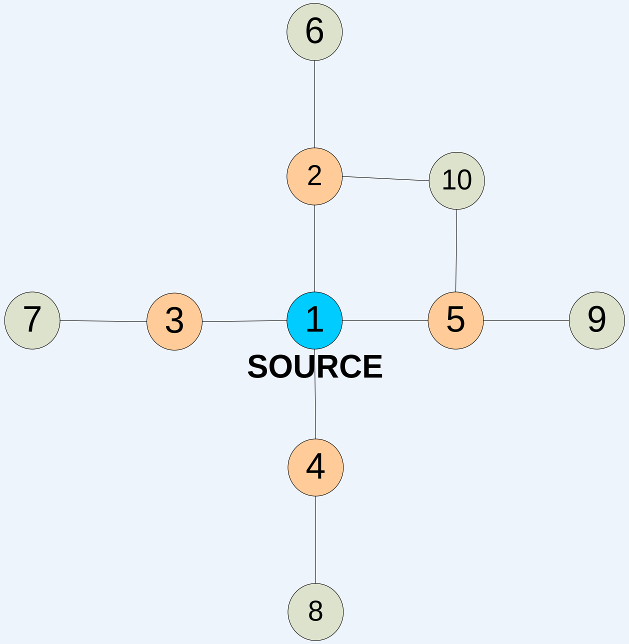


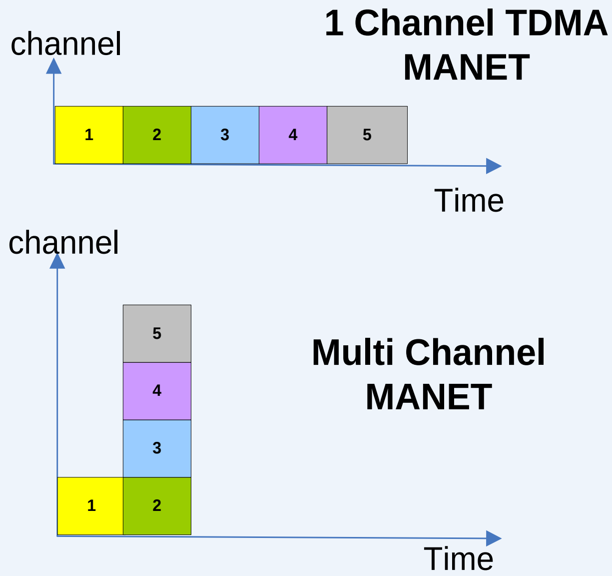
MCR F/TDMA MANET





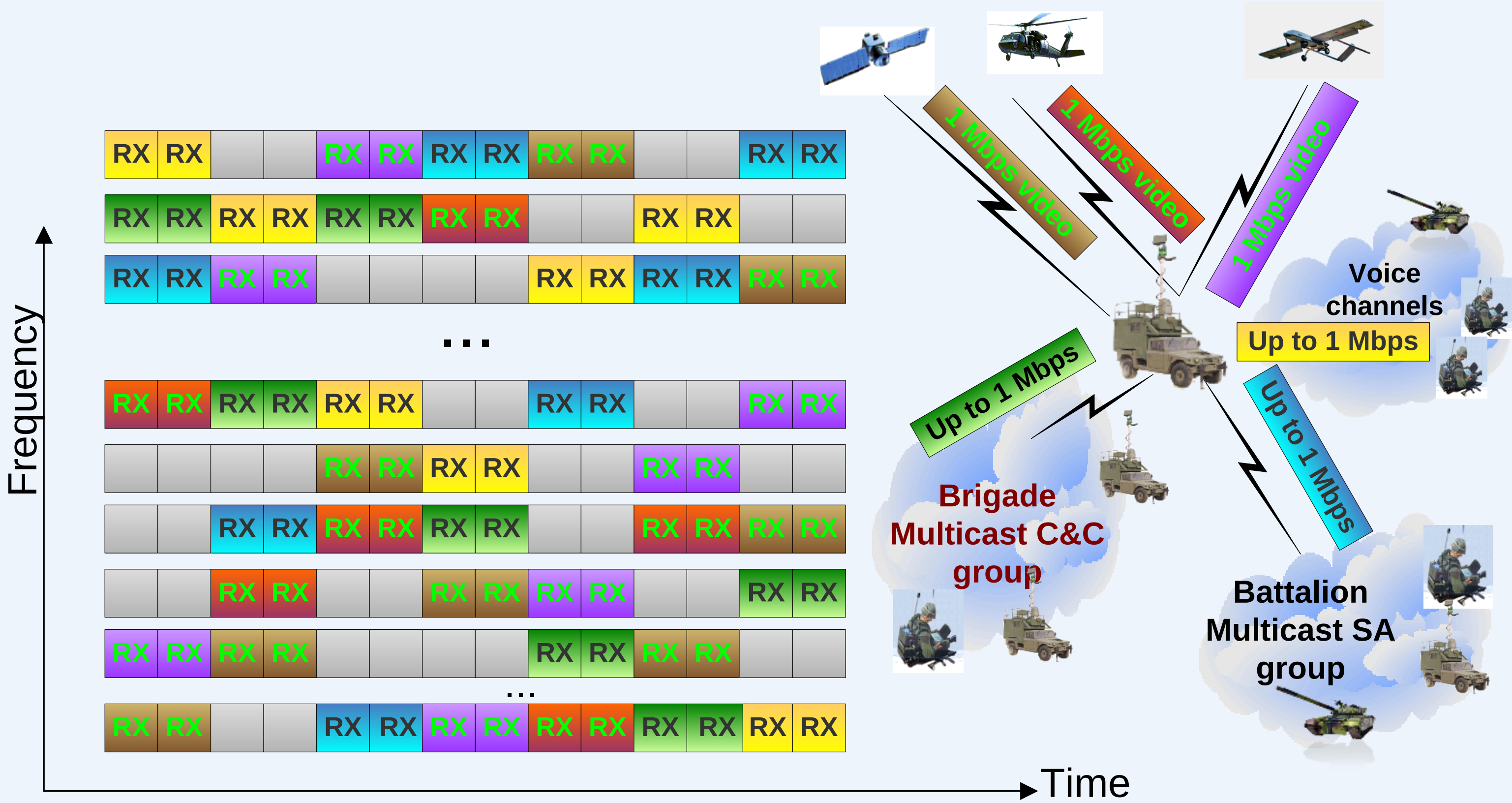
Shorter Delay when Routing delay critical services (Voice, Video)





- MCR - No delay
- 1 Channel - 3 frames max, 1.5 frames average

MCR F/TDMA – Combining different Comm. Services

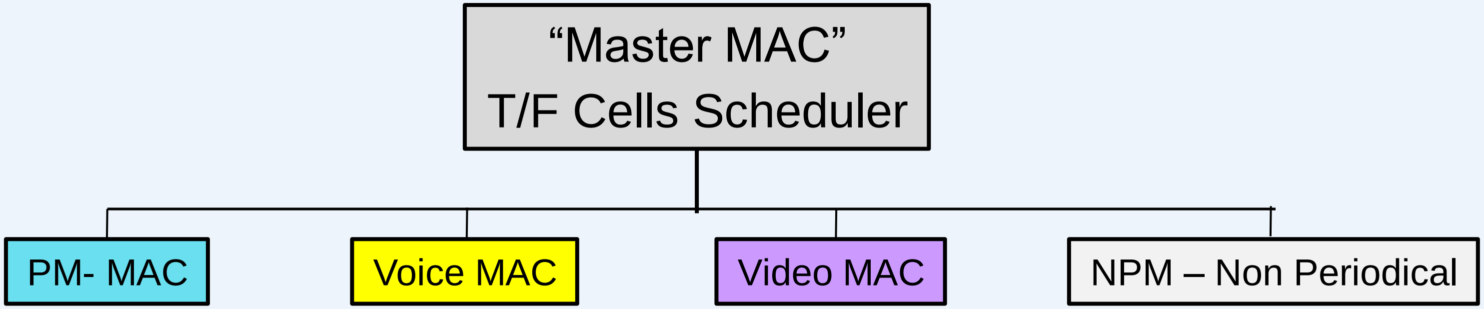


Reception of several frequency-hopping channels with **No Tradeoff !!**

Total received data ~ 6 Mb/s ~ Sum of Tx rates ⇨ (# Channels)X Channel rate

The Data Rate is bounded only by the rate of the transmitters

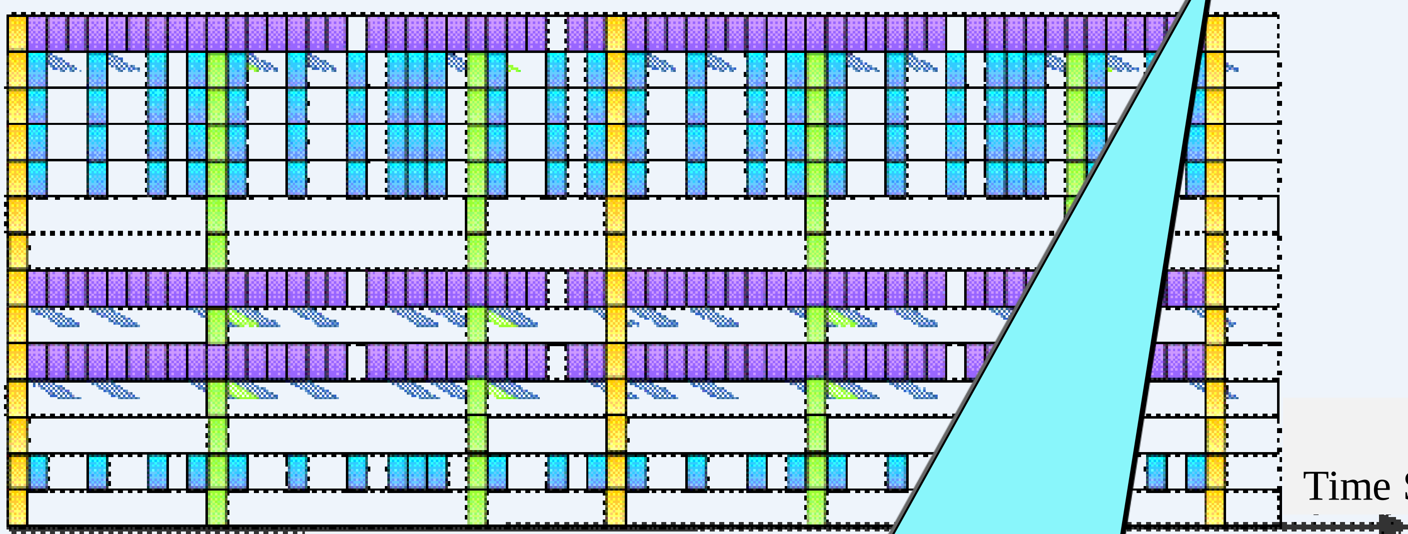
MACs for different communication services



- **Each service type has different QOS and Routing/ Relaying requirements -**
  - ✓ Broadcast, Multicast, Unicast.
  - ✓ Delay critical or latency tolerant.
  - ✓ Broadcast Relaying (for "Combat Voice") or N- Hop routing (OLSR).
  - ✓ Rate guarantee (PM) or End to End Guaranteed Delivery (commands, etc.)

TFC Scheduling by Service type

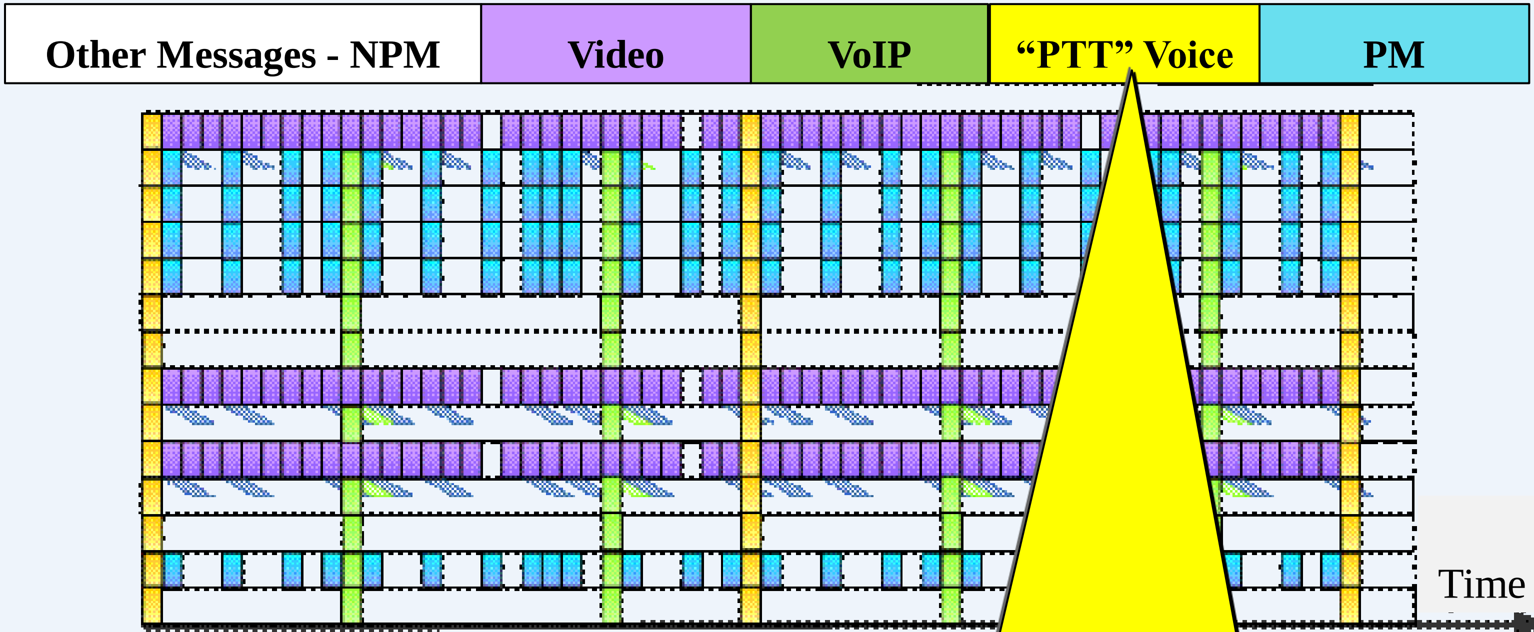
Other Messages - NPM	Video	VoIP	“PTT” Voice	PM



Periodical Refreshing Messages - for SA, CA, and control messages (Area context)

- Delay sensitive, need Assured message rate
- Adjustable reliability using FEC.
- Broadcast N- Hop Relaying.

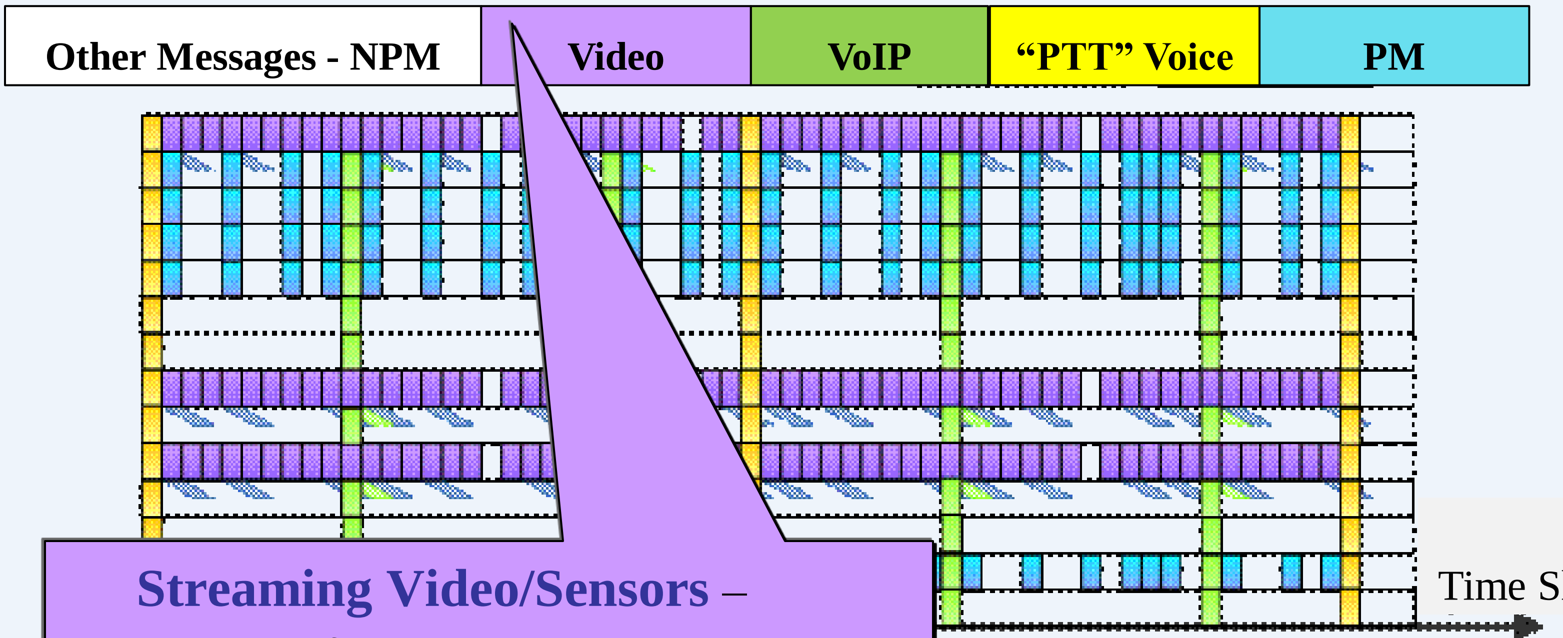
TFC Scheduling by Service type



"PTT Combat Voice" - Critical Delay.

- **Dedicated channels and time-slots.**
- 1 Channel = Several Voice Multicast Groups. (Since 1 voice session is ~ 4 Kb/sec, a 1 Mb/sec channel can supports several sessions).
- Broadcast 1-Hop Relaying (OLSR).

TFC Scheduling by Service type

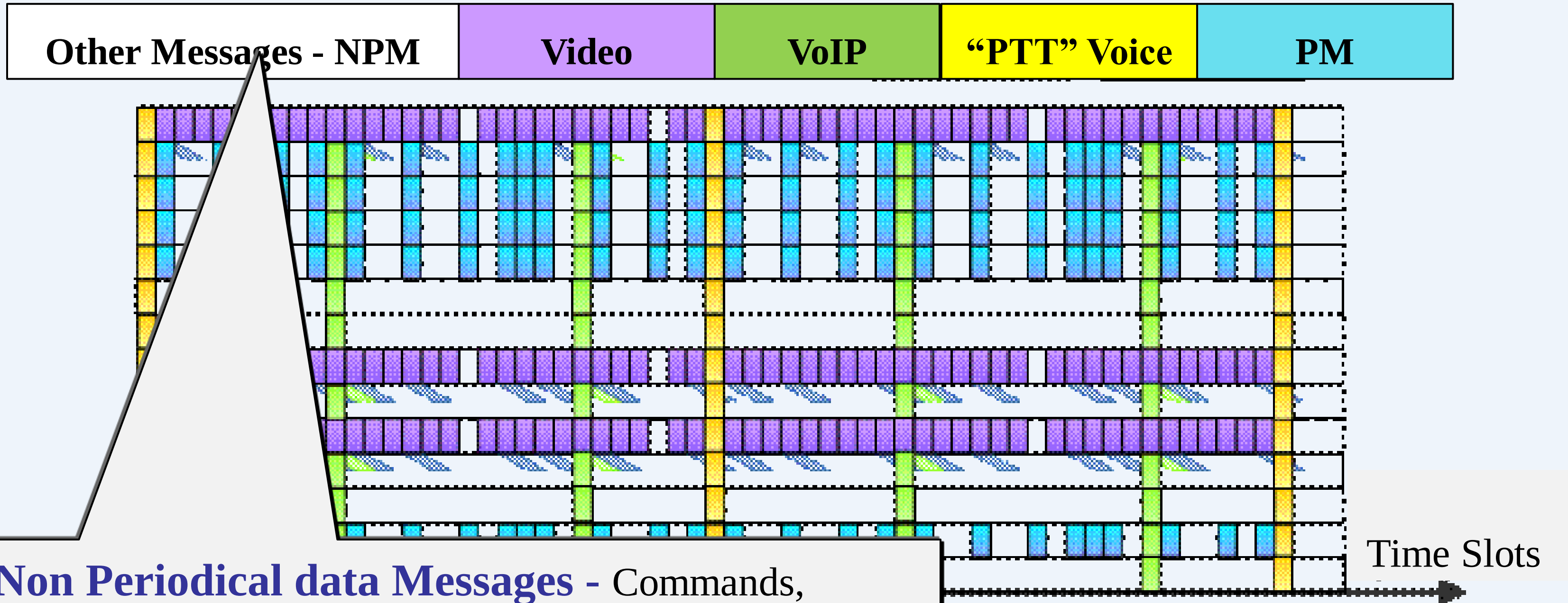


Streaming Video/Sensors –

Relatively few Sensor nodes per area.

- <u>Can suffer small delay</u>.
- Depending on compression and resolution, 0.25 – 1 Mb/s per stream = > 1 MHz channel per sensor.
- UC, MC or BC. Up to 1 Hop relaying.
- Time Slots "Punctured" for Voice + PM reception (at reduced rate).

TFC Scheduling by Service type

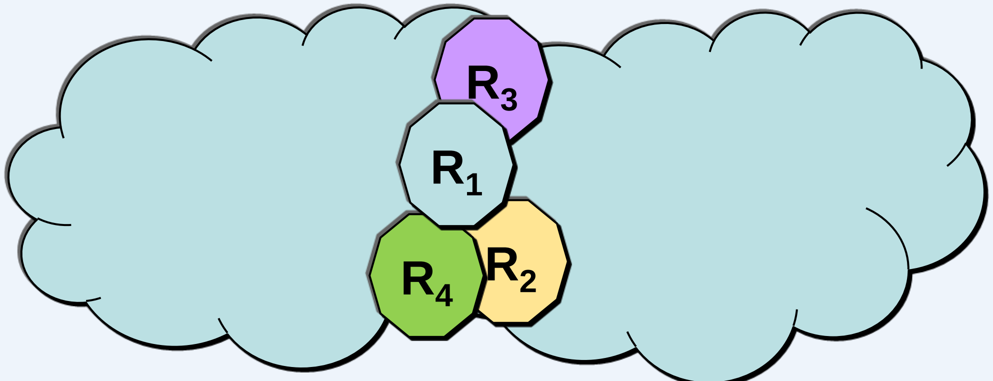


Non Periodical data Messages - Commands, Reports etc. **(Units or Functional group context)**

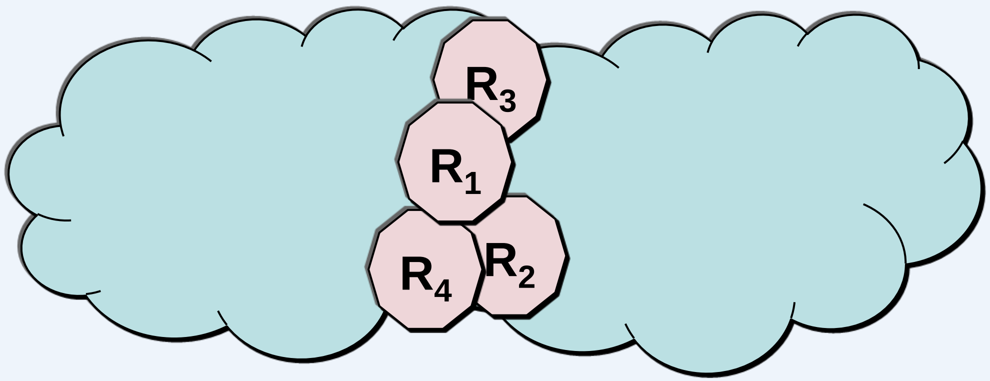
- On-demand variable-length messages, Unicast or Multicast.
- Delay insensitive.
- Many-Hops routing + Delivery Guarantee is needed.
- TFCs allocation is in all TFCs not constrained by PM, Voice, Video.

Routing advantages of MCR

- **Single Channel Manet** – **R_1 , the only "blue channel" node that Rx both sides of its net, is a bottleneck Relay**; although $R_2 \div R_4$ are within 1-HOP range of both sides of the blue net, they aren't tuned it and can't relay. **Relay Bottleneck!**

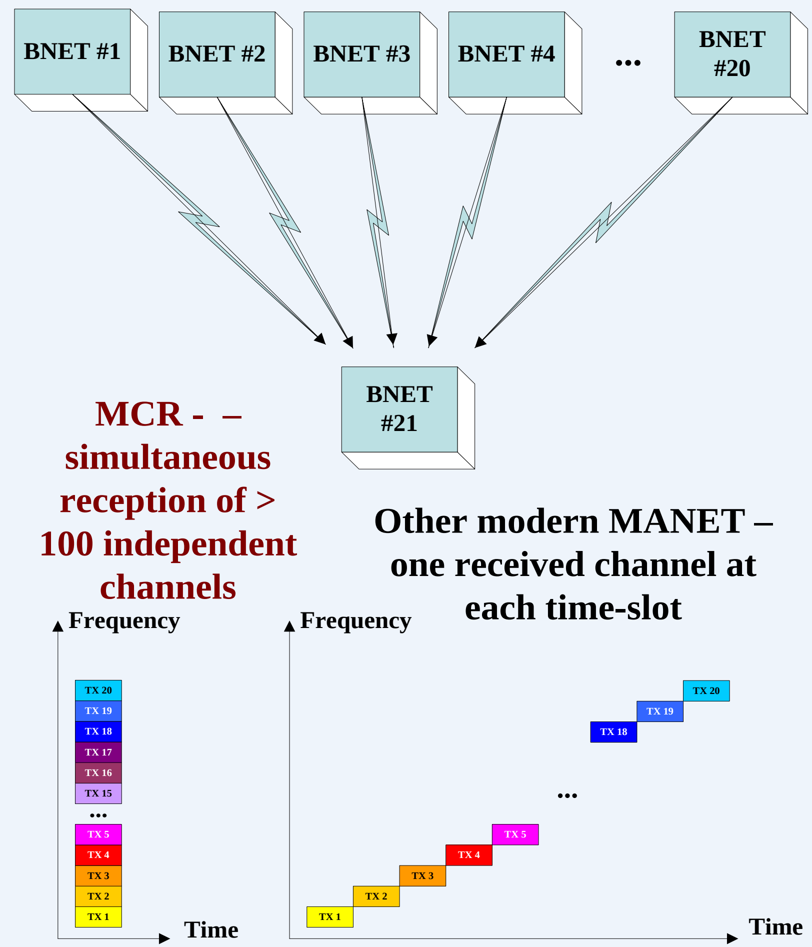


- **MCR Manet** – All nodes Rx all channels ⇨ 4 nodes can relay – **No bottleneck, better flow-control**



Summary - Advantages of Multi Channel Reception MANET

- A breakthrough in network capacity, scalability and delays
- Less overhead - less Relays, Negotiations, Reservations
- Simpler network planning
- Quick force merge, split & pass- through – Reconfiguration not needed.
- More performance in much less hardware
- Cognitive ready – each SDR is a “continous” Spectrum Analyzer



The BNET Multi-Channel Reception SDR Family

Breakthrough network Capacity, Delay, Scalability - Data, Video, Voice on the move

BNET- Airborne

4 Rx Bands in 30-2000
2X50 W Internal Transmitters
Manet +AM/FM+ UHF Satcom
11 Kg, ½ ATR (35X19X13 cm)
Tx =Rate: up to 10 Mb/s
Rx Rate: > 200 Mb/s !

BNET- Vehicular

2 selectable Rx Bands
1 50 W Tx
Manet + AM/FM
8 Kg, 30X20X10 cm
Tx =Rate: up to 10 Mb/s
Rx Rate: > 200 Mb/s

BNET- Hand Held

1 selectable band
Manet or AM/FM
5 W Tx, 1.2 Kg
Tx =Rate: up to 2 Mb/s
Rx Rate: 20 Mb/s
(A 4 Kg, 2 Bands, 20 W, larger battery Manpack will also be available)

- Different Chasses & Cooling
- Identical RF, DPU, SBC Modules

Thanks For Your Attention !

Questions?

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[2] L. Bao, "MALS: Multiple Access Scheduling Based on Latin Squares", In MILCOM 2004 - IEEE Military Communications Conference, no. 1, Oct 2004, pp. 426-426.

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[4] R. Rozovsky and P. R. Kumar. "SEEDEX: a MAC protocol for ad hoc networks". In Proc. of the 2nd ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc) 2001, pages 67–75, Long Beach, CA, USA, Oct. 4-5 2001.

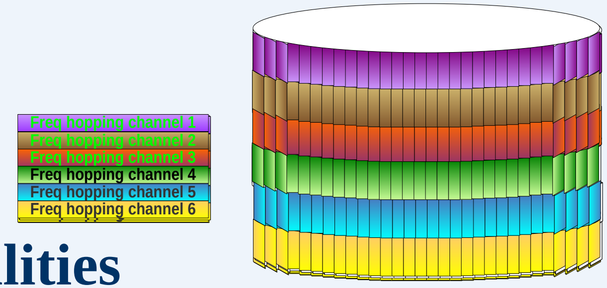
[5] M. Wermuth, Y. Wermuth, M. Weiss, S. Avadis, Y. Fuchs, "An Improved Mobile Ad-Hoc Network", Pending Patent application # IL216282, Dec 2011.

[6] S. Avadis, A. Lerner, Z. Nutov, "MMM: multi-channel TDMA with MPR capabilities for MANETs", Wireless networks magazine, Vol. 18 No. 5, July 2012. Available online from Springer as DOI 10.1007/s11276-012-0468-6.

Backup Slides

The BNet MANET WF
Mitigating the Spectrum challenge

- **Easy and simple pre-planning**:
  - Nets are Multicast groups, not frequencies
  - Given a spectrum allocation and QoS requirements, The net dynamically utilizes only the needed channels to meet the QoS requirements efficiently



- **Highly efficient automatic multi-rate capabilities**
  - Utilize the ultra wideband receiver as a rate sensor
  - Automatically adapt the data rate (from BPSK/QPSK to 64QAM)