Radar and Electronic Warfare Cooperation

How to improve the System efficiency?

Stéphane KEMKEMIAN, Myriam NOUVEL-FIANI
BU Radar and Warfare Systems, Technical Directorate
THALES Airborne Systems
Elancourt, FRANCE
stephane.kemkemian@fr.thalesgroup.com,
myriam.nouvel@fr.thalesgroup.com

Eric CHAMOUARD
BL Electronic Combat Systems
THALES Airborne Systems
Elancourt, FRANCE
eric.chamouard@fr.thalesgroup.com

***Abstract*— Up to now, combat aircrafts are fitted with Fire Control Radar (FCR), Electronic Warfare System (EWS), and some radio links. Each of these systems is dedicated to a particular task and the cooperation is reduced to a minimal exchange of information between them, so far. Major system performance enhancements are to be expected from close co-operations to each other sensors. The future co-operations can be ordered in four stages. The first three ones lead progressively to a multi-functions sensor. The last one is the deployment, on a given platform, of compact multi-functions sensors on a network basis. Another area of co-operation is the realization of R.F. functions that are currently provided by other devices using other antennas. A typical example is the implementation of data links using the Radar or the EWS**

I. Introduction – The main actors

Currently, the platform, which is considered, is a manned combat aircraft. In the future, this could also be an UCAV (Unmanned Combat Air Vehicle). In this paper, we call this platform by the generic name "aircraft" (A/C).

A. The Fire Control Radar

The FCR (Fire Control Radar) onboard an aircraft is usually operated in active modes to detect Range even classify Air or Surface targets. On the one hand, it provides fine discrimination and accurate locations of targets (Range, direction and velocity) by processing the echoes reflected by these targets. These features make it an efficient sensor in a dense environment of targets. On the other hand, its main drawback is that it transmits signals that can be detected by an adversary RESM (Radar Electronic Support Measurement).

Many studies have been conducted to develop discrete waveforms with low Probabilities Of Intercept (POI) against an adverse Electronic Warfare System (EWS). However, the main challenge is to reduce significantly the POI without dramatically reduce the detection Range of the Radar. This task remains difficult due to the technological progresses of both EWS receivers and processing ("narrow" band digital multi channels receivers and efficient pulses de-interleaving algorithms).

The new FCR, now fitted with Active Electronic Scanning Antennas (AESA) operating in X-band, have a bandwidth much wider than the previous FCR fitted with "classical" antennas. Since these AESA are currently planar arrays, their angular coverage is limited to the aft sector (around ±60°) both in azimuth and elevation.

The FCR is also a powerful transmitter (EIRP in excess of 60 dBWi), has a narrow pencil beam (some degrees) and the antenna gain is usually more than 30 dBi, depending on the antenna size. Thanks to the flexibility of AESA, various radiating patterns can be formed; both on transmit (by acting on the phase and gain of the T/R modules) and on receive (by using adaptive or non adaptive digital beam forming).

B. The Electronic Warfare System (EWS)

On the contrary, the RESM part of the EWS is a passive and covert sensor. It provides detections and accurate angular location about targets by receiving and processing their EM transmissions coming from radars. The RESM can also identify the Radar carried by the target.

On moving targets, like air targets with unknown trajectory, the target Range is derived from received level of signal that depends on the exact radar beam steering and other uncertainties on the adverse radar. This Range measurement is poor; in fact the relative accuracy is of some tens of percents.

On non-moving targets like non-mobile ground targets, this accuracy can be greatly enhanced by analyzing the relative angular variation of the target along a significant A/C movement.

The sensitivity of a RESM receiver is much lower than a Radar one: it cannot make use of *a priori* information on the signal to be received as a Radar does. Furthermore, in a dense environment, it has to separate the different transmissions coming from numerous radars and counts them. The higher is the receiver sensitivity, the more difficult is the separation of

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the different pulses coming from a lot of radars in a dense and complex environment.

Despite a lower sensitivity the RESM detection Range is usually greater than the FCR one. That is mainly due to an R^{-2} propagation factor (one way) for the RESM, compared to the R^{-4} factor for the Radar (two ways), and the progresses in term of RCS reduction of the facing A/C.

On the one hand, the EWS operates over more than three, even four octaves, and it coverage is "all sectors" (360°) thanks to a set of antennas system distributed around the A/C. On the other hand, the antennas gains are much lower than the one of a FCR: the goal is to minimize the number of antennas that is required to covert 360°. The EIRP of the RECM (Radar Electronic Counter Measures) part of the EWS is much lower than the one of the FCR, but it is a wide band transmitter system with a large flexibility in term of coverage and modulations.

II. Co-operations with FCR and EWS

They are mainly at four levels:

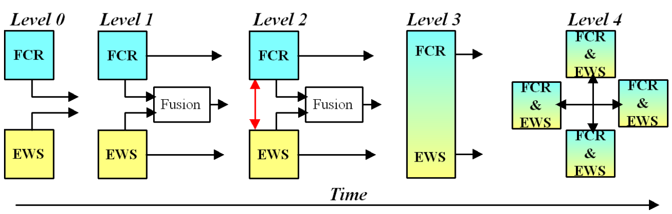

Figure 1. Four levels of FCR/EWS co-operation.

0. **Level 0**: For a very long time, the main co-operation between FCR and EWS has been to avoid mutual interference. A time sharing is established for organizing Radar transmissions, Radar Warning surveillance and RECM. In fact, whatever the level of co-operation is, the time sharing issue remains and shall be considered up to fourth level of co-operation. This point is discussed in section III.
1. **Level 1**: Cooperative approach based on data fusion from both FCR and EWS to achieve common functions more efficient than those undertaken by one or the other system separately (FCR and EWS).
2. **Level 2**: Mutual enhancement using mutual exchange of raw data between the sensors.
3. **Level 3**: Common sub-system such as antenna, exciter, receiver and processing. These common sub-systems are used for both FCR and EWS functions:
   - Sharing of Exciter: low phase noise exciter for both systems.
   - Sharing of Receivers: High dynamic range receivers. Multiple band receivers.
   - Sharing of antennas.
4. **Level 4**: Compactness and smart sensor deployment of a network including dual function sensor FCR and EWS. Sharing of new resources between the two systems FCR and EWS.

Another kind of co-operation is the realization of RF functions that do not exist or are currently provided by other devices using other dedicated antennas and RF parts. A typical example is the implementation of data links using the Radar or the EWS or both of them.

III. Time/Frequency Sharing issue between FCR and EWS

The issue is the R.F. coupling from the FCR to the EWS[1]. It occurs by two main mechanisms:

- Close coupling aboard the A/C between the FCR and EWS antennas;
- Coupling through the ground clutter and possibly hydrometeors in case of heavy rain.

A. Coupling aboard the A/C

This coupling occurs through the side lobes, both those of the Radar antenna and of EWS antennas. Assuming that the levels of the side lobes of all antennas are close to 0 dBi, the coupling can be estimated as follows: $g = \lambda^2 / 4\pi d^2$, where d is the spacing between antennas.

In X-band, the coupling is about –70 dB with d = 5 to 6 meters. The radiated power of an AESA/FCR is about 60 to 70 dBm (depending of the number of T/R modules). The order of magnitude of the spurious signal received by the ESM is around 0 dBm: without any R.F. front filtering such a signal level totally blinds an ESM and no ESM reception is possible during the transmission of the FCR pulses.

B. Coupling through clutter

A coupling signal through the clutter occurs due to the reflection of the Radar signals on ground or atmospheric particles. Depending on the A/C altitude, FCR antenna tilt, the kind of the terrain flied over, etc., this coupling:

- May be non significant on ESM reception;
- May desensitize the ESM reception;
- May blind the ESM reception.

The two last points require a time and/or frequency sharing between Radar functions and ESM functions to ensure that both systems work with sufficient efficiency. In the following developments, the level of sharing will be detailed for each co-operation.

IV. Level 1: Data fusion

One typical example is the Non Cooperative Air Target Recognition (NCTR).

A. Radar NCTR

The NCTR methods in operational use are based on the engines characterization. Indeed, the low pressure compressors modulate the Radar echoes: the result is characteristic spectral signatures. This effect is well known as

[1] The problem of the compatibly between simultaneous jamming and Radar functions is not addressed here.

"Jet Engine Modulation" (JEM). This technique may lead to ambiguous recognitions: for instance several A/C fitted with the same or similar engines. New upcoming enhancements consist in adding a range profiling analysis (RP). The merging of both methods reduces the ambiguities but some of them remain.

B. RESM NCTR

The EWS identifies a platform by its R.F. emissions, namely the radar transmissions. So, an EWS identifies a platform by its Radar and more precisely by its Radar waveforms. As said previously, this method cannot identify the platform without any ambiguity: one type of radar may fit several types of A/C.

C. Toward a "System NCTR"

The goal of the "System NCTR" is to identify the platform with the least possible ambiguity. To achieve that, the System NCTR merges:

- A class of A/C that carry engine(s) in the list of possible engines (Radar/JEM);
- A class of A/C that match the Range Profile (Radar/RP);
- A class of A/C that carry radar(s) in the list of possible radars (RESM/radar identification).

Thus, simultaneous FCR and ESM functions are desirable. So, a time or a frequency sharing between the two systems is required.

V. Level 2 – Mutual information exchange

Two examples of co-operation at this level are given:

A. Mutual contribution of FCR and EWS

This example deals with an Air to Air task. It is the cooperative detection and discrimination of air targets using both sensors: indeed, airborne Radar is carried by an aircraft!

Today, as stated in section I.B, a RESM detects and identifies discreetly at long Range transmitting radars only when their main lobes illuminate it. In multi-targets situations with close angular co-location, a main issue is the knowledge of the number of platforms. This is particularly critical in the case of multiple platforms fitted with the same Radar. Even it is not possible if Radars are in a silent mode.

On the contrary, the FCR is an efficient multi-target sensor (discrimination using the range, the Doppler and the angular selectivity of its antenna), but with usually a lower detection range than the RESM. However, the FCR detection Range can be improved if the angular domain of detection search Ω is reduced (the Radar detection Range R is proportional to $\Omega^{-1/4}$).

In the present scheme, the RESM provides the radar with the direction of its "raw" detection. The FCR does briefly its search in a small angular area only in the vicinity of this direction with enhanced sensitivity. In return, it provides the EWS with the number of detected targets and their accurate locations (Range, Angle and Speed), so the previously mentioned ambiguity is removed and the TSA (Tactical Situation Awareness) is improved.

B. Contribution of EWS to FCR

This example deals with an Air to Ground task. An example of such a co-operation is the Suppression of Enemy Air Defense (SEAD) in Air to Surface operations.

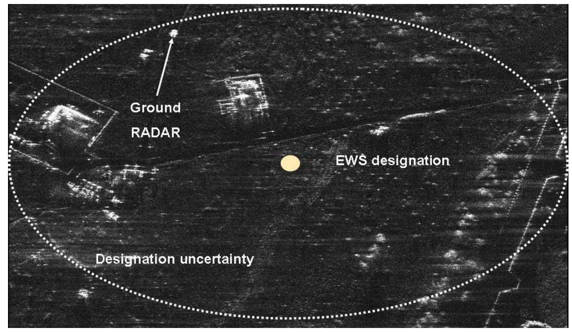

Figure 2. Example of contribution of EWS to FCR: the SEAD.

1. At first step, the ESM part of the EWS provides the Radar with a "coarse" location of ground enemy radar. The ESM location uncertainty is an ellipsoid where the threat is located, Figure 2.
2. At second step, the FCR performs a SAR image centered on this ESM designation. The SAR image size is matched with the EWS location accuracy.
3. The third step is the detection of the radar, which is characterized by a special signature on the SAR image and can be detected by using a special processing.

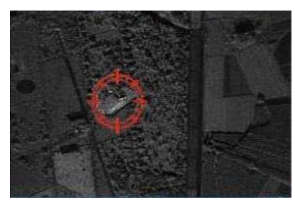

Figure 3. Accurate target location by the FCR.

4. The fourth step consists in an accurate location of the target in geodesic coordinates by the FCR.

This co-operation allows the use of low cost missiles without any seeker (low cost air to ground fire control). The final guidance to the target is only provided by the missile navigation system using an INS/GPS unit.

In the two previous examples (sections A and B), the ESM and FCR systems work sequentially: there is no time/frequency sharing issue between them.

VI. Level 3 – Common subsystem

There are two sub-levels:

1. Sharing of resources to achieve more performing common function than today.
2. Sharing of building blocks to reduce the cost of the global "EWS + RADAR" system.

A. *Sharing of resources*

An example is the improvement of the RESM sensitivity in X-band. Nowadays, as stated in section I.B, the RESM sensitivity is limited (in term of dBmi) and only allows detecting radars signals when their main lobes illuminate the EWS.

An improvement is to connect the RESM receiving system to the high gain AESA of the Radar. In doing that, the RESM sensitivity (-dBmi) is greatly enhanced, but only in the direction of the main beam of radar AESA, see Figure 4.

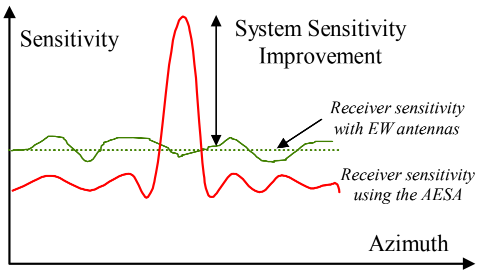

Figure 4. RESM sensitivity improvement in X-band.

This improvement allows the continuous detection of Radars both in their main lobe and also in their side lobes. That is a significant improvement, both in term of sensitivity and in term of separation and count. A new scanning strategy dealing with both the frequency and spatial domain needs to be developed, the classical one using only the main lobes and a frequency exploration having too much limitation.

Obviously, this improvement applies only to X-band radars having the same polarization than the AESA one. The time and/or frequency sharing issue between FCR and ESM does not exist since the ESM system make use of the the FCR antenna.

B. *Sharing of building blocks*

At this level, several common building blocks may be shared between the EWS and the FCR. A non exhaustive list of possible common building blocks is given hereafter [1],[2]:

- High gain, wide bandwidth X-band active array with multiple sub-arrays ; Low/medium gain wide band antennas;
- Tunable RF filters, RF and IF switches;
- Down converters and Up converters;
- Multi-modes digital IF receivers;
- Frequency synthesis, Wide/Narrow band Waveform Generators;
- Power supplies.

The aim is to reduce the useless duplication of common elements, thus the cost and the size [3]. Nevertheless, simultaneous functions (Radar detection, RESM and RECM) must remain feasible. To allow this, common building blocks will have to be duplicated. The reliability of the global system must be also considered.

VII. Level 4 – Network of Multi Functions Sensors

An old Radar dream is to look, not only toward the aft sector, but also toward the A/C side directions. The EWS function is also interested in having high gain and wide band AESA. Until now, these Radar and EW capabilities did not exist because of the lack of appropriate technologies. Nowadays, technologies are developed and existing, especially broadband AESA and related R.F. technologies.

Two examples of broadband, thin radiating structures that are able to perform wide angular scan and exhibit multi-polarization capacity are shown in Figure 5.

All of them use a tile structure. As they are broadband and dual polarization AESA, they are intended both for Radar application and EW functions.

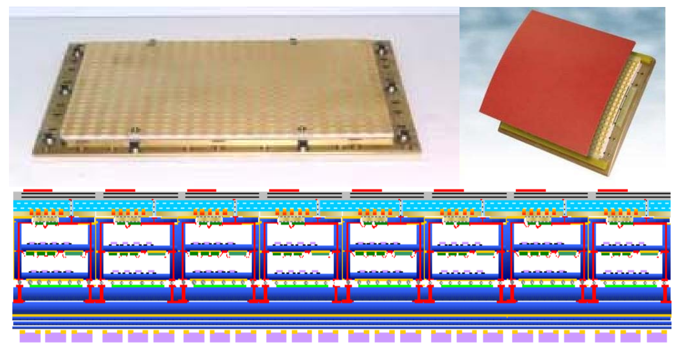

Figure 5. Planar and conformal broadband tile arrays.

This kind of technologies can be carried out on several concepts. Some of them are described hereafter:

A. *Aboard a single platform*

Two typical examples are:

1. A Networked Combat Electronic Systems (NCES) for UCAV;
2. An enhancement of the F/POLE - A/POLE maneuver to prevent a fired target to riposte;

1) *Networked Combat Electronic System for UCAV*

The NCES is an example of network of multiple functions sensors aboard UCAV platforms (*cf.* Figure 6.).

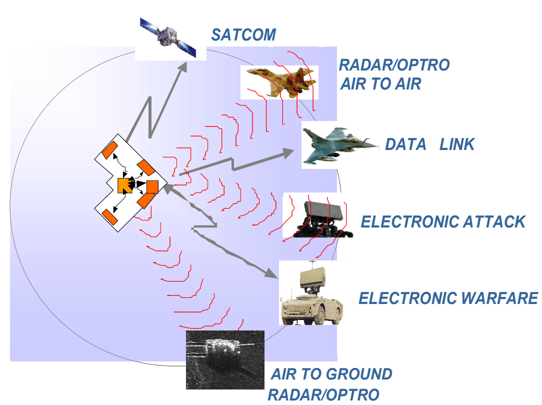

Figure 6. NCES concept.

The concept consists in implementing aboard a platform such an UCAV several distributed broadband AESA and related front end R.F. sub-systems that perform all the R.F functions[2] of the platform:

- ESM functions with a coverage of 360° and a very accurate goniometry;
- Radar functions (both Air to Air and Air to Surface);
- Jamming functions.

The central core in Figure 6. carries out the following tasks:

– Management of the multiple multifunction AESA systems (supervision, scheduling, priority management). For example, functions such as 360° coverage passive surveillance requires the coordination between all side antennas, whereas other functions like air to air radar tracking mode can work with only one antenna, independently from the others antennas.

– Reconfigurable middleware based on FPGAs components (digital receivers, waveform generator, high speed digital processing);

– All the processing (signal processing, data processing);

– Interface with the Man Machine Interface of the platform.

2) Enhanced A-POLE/F-POLE escape maneuver

An active missile fired at long range requires an initial guidance till its seeker locks on the target and becomes autonomous. The initial guidance is provided by the FCR tracking.

After the missile firing, another operational requirement is to carry out an escape maneuver to avoid the riposte of the enemy target. The escape maneuver is limited by the need to track the target until the missile seeker is locked-on. In other words, the target must remain in the Field Of View (FOV) of the FCR. With "conventional" nose radars, the FOV is limited to about ±60° relative to the A/C longitudinal axis. This is a potential vulnerability because the "friend" fighter remains detectable by the enemy FCR.

An improvement would be to maintain the tracking with a constant relative azimuth of 90° until the kill of the target. In this manner, the enemy fighter cannot riposte because the "friend" fighter remains in its Doppler notch, Figure 7. This strategy needs:

- A radar tracking up to at least 90°, for instance by using the multifunction side looking arrays, Figure 5.
- An accurate guidance to maintain the "friend" fighter in the Doppler notch of the enemy FCR whatever the enemy A/C maneuvers are. This task can be carried out with the ESM measurements on the enemy FCR thanks to the same multifunction broadband side looking arrays.

[2] The data-link functions are not evoked in this sub-section, since the section VIII is entirely dedicated to this subject.

Unlike previous examples, the compatibly issues between both FCR and ESM system is critical since most of FCR operate in X-Band.

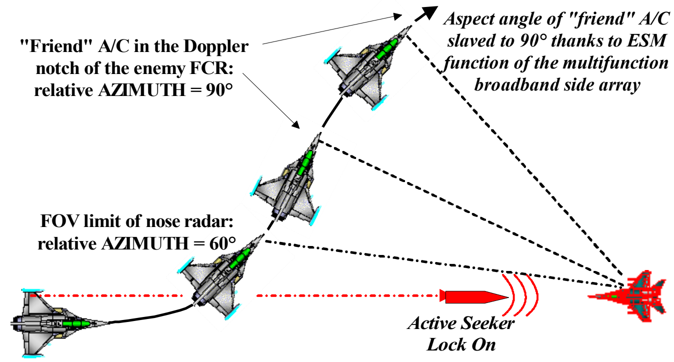

Figure 7. Enhanced A-POLE / F-POLE escape maneuver.

B. Dual functions sensors aboard multiple co-operative platforms

An example of multiple platforms task, which can be efficiently carried out by dual functions sensor is the passive target location using the DTOA (Differential Time Of Arrival) technique.

1) Multiple platforms enhanced DTOA

A RESM system aboard a single A/C cannot measure accurately the range of a moving target like another A/C (cf. section I.B). Indeed, the range is derived from the received power and this method is subject to very large uncertainties.

In order to provide both an instantaneous and accurate range measurements, even on a moving target, a solution is to use the DTOA technique with at least three cooperative platforms, Figure 8. The pulses coming from the radar to be located are received and dated with a common clock, which can be provided, for instance, by using GPS signals.

An issue is to be sure that the received pulses that are used come from the same Radar and the same transmitted pulses. To ensure that, both sensitivity and good discrimination behavior are required. A solution that fulfills these conditions is to provide each RESM with a high gain and narrow beam antenna, Figure 4. Such an antenna can be the AESA of the nose FCR.

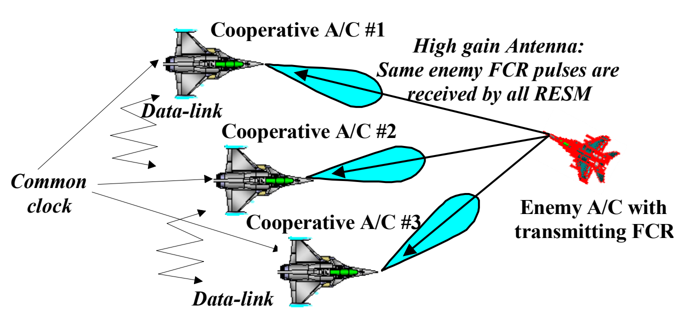

Figure 8. Cooperative multiplatform DTOA with high antenna gain.

Such a co-operation needs a data-link between the platforms. The data-link can use the side looking multifunction broadband arrays as in Figure 5.

VIII. Other co-operations: communications

For more than twenty years, FCR have been performing communications functions for active missiles guidance purposes prior to the active seeker lock-on.

For tactical situation exchanges, the platforms are usually networked with some specific data-links such as the "L16" data link. However, due to interoperability constraints, such broadcast data-links are not well suited for emerging functions. So, other "*ad-hoc*" data-links are required. In order to reduce the number of antenna apertures or avoid the use of pods that can reduce the weapons load, the re-use of RF sub-systems (both Radar and EWS) is an interesting solution for communication purposes.

A. Data rates cases

There are mainly three cases to be considered:

1. **Low data rate** links (tens of kbits/s). The main uses of such links are the exchange of tracks (Radar and RESM) between A/C. An example of such co-operation between A/C is a very accurate 2D target location in GMTI radar mode (both in X and Y axis) [4]. Other applications may be, for instance, tactical information exchange with ground and UAV Control and Command (C2).
2. **Medium data rate** links (order of tens Mbit/s). A typical application is the transmission of small image (optical or SAR) toward ground or toward other A/C in the operations theater, Figure 9.
3. **High data rate** links (some hundreds of Mbit/s or more). The foreseen applications are the transmission of high resolution images, even video sequences (Up-Link and Down-Link) with the ground or between other A/C. One goal is to send high resolution images to a Command and Control Center (C3) to identify objectives to be treated; then to send back them with specified targets to hit.

Figure 9. Small image transmission to ground

B. Sub-system involved in

Specific Modems are required. The discussions related to the Modems are beyond the scope of this paper. Here we are focusing only on the sub-system of the ensemble (EWS + FCR) involved in the communication functions.

1) Intra-flight data-links

The first two cases are mainly related to intra-flights exchanges. They need to be operated in all directions relative to each A/C. As moderate data rate are required, the most suited way is to use the RF and antenna sub-system of the EWS.

2) Extra-flight data-links

The third case needs very high data rates and, most often, at long Range (between the stand-off C3 and the A/C in the theater). A large EIRP (Equivalent Isotropic Radiated Power) is thus mandatory. The most suited sub-system to do that is the powerful and wideband X-band nose radar fitted with an AESA. In a second phase, the multifunction wideband arrays described in section VII will be able to extend the azimuth operating domain of such data-links and avoid the aircraft to perform certain maneuvers for the receiving station is in its Field Of View.

IX. Conclusion

This paper deals with Radar and EW co-operation onboard manned combat aircrafts (UCAV in the future). In a general case, this concept improves the efficiency of A/C systems containing both Radar and EWS. Four different levels of co-operation were addressed by growth of degrees of co-operation: Data fusion, Mutual Information Exchange, Common subsystem and network of dual functions sensors. The Radar and EW co-operation can also be extended to multiple co-operative platforms. Moreover, co-operation can also be beyond the only EW/FCR co-operation. It can also be EW-FCR and other R.F functions, such as communication.

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